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WASTEWATER DECHLORINATION

STATE-OF-THE-ART FIELD SURVEY AND PILOT STUDIES

by

Ching-lin Chen
Henry B. Gan
Sanitation Districts of Los Angeles County
Whittier, California 90607

Contract Nos. 14-12-150 and 68-03-2745

Project Officers

Albert D. Venosa
Irwin J. Kugelman
Wastewater Research Division
Municipal Environmental Research Laboratory
Cincinnati, Ohio 45268

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
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Project Officers: Albert D. Venosa (513)684-7668
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16. ABSTRACT

A study of dechlorination was conducted in the County Sanitation Districts of Los Angeles County to determine the utility and efficiency of the sulfur dioxide method and to provide a cost-effectiveness comparison of sulfur dioxide and two other methods of dechlorination, namely, activated carbon and holding tank processes. Study objectives were accomplished through three main phases of work: literature review, pilot-scale testing, and full-scale evaluation in the field.

The pilot-scale testing indicated that no degradation of physical and chemical water quality occurred in the dechlorinated effluents from any of the three dechlorination processes investigated. However, a one to two order of magnitude increase in total coliform density in the 10-minute samples following dechlorination was commonly observed among the three dechlorination processes. The increase seemed to originate from contamination by the existing microorganism communities in the dechlorinated effluent rather than from the reactivation of injured bacterial cells.

The field survey involved the canvassing of 55 operating plants in California by mail, telephone, and site visits to selected facilities. Although overdosing of sulfur dioxide was frequently necessary to meet the residual chlorine discharge standards, most installations found pH adjustment and reaeration of the dechlorinated effluent unnecessary. Process cost estimates indicate that sulfur dioxide process is the most cost-effective method for dechlorination.

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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem .

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that reserch and provides a most vital communications link between the researcher and the user community.

This report describes the efficiency and cost-effectiveness of the sulfur dioxide dechlorination process required to minimize the toxic effects of chlorine and chloramines of the chlorinated effluents from municipal wastewater treatment facilities upon the aquatic environment.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

A study of dechlorination was conducted in the Los Angeles County Sanitation Districts to determine the utility and efficiency of the sulfur dioxide method and to provide a cost-effectiveness comparison of sulfur dioxide and two other methods of dechlorination--activated carbon and holding tank processes. Study objectives were accomplished through three main phases of work: A literature review, pilot-scale testing, and full-scale evaluation in the field.

The literature review involved an extensive search on the practice of dechlorination in the United States and abroad, an assessment of the need for reaeration and pH adjustment in the dechlorinated effluent, and an examination of the extent of bacteriological aftergrowth in outfall pipelines and receiving waters.

The pilot-scale testing indicated that no degradation of physical and chemical water qualities occurred for the dechlorinated effluents from any of the three dechlorination processes investigated. However, a 1 to 2 orders of magnitude increase in total coliform density in the 10-minute samples following dechlorination was commonly observed among the three dechlorination processes. The increase seemed to originate from the contamination by the existing microorganism communities in the dechlorinated effluent rather than from the reactivation of injured bacterial cells.

The field survey involved the canvassing of 55 operating plants in California by mail, telephone, and site visits to selected facilities. The feed forward method of sulfur dioxide dosage control with signals received from both a flow and residual chlorine controller appeared to be the most commonly employed method. Although overdosing of sulfur dioxide was frequently necesssary to meet the residual chlorine discharge standards, most installations found pH adjustment and reaeration of the dechlorinated effluent unnecessary.

Process cost estimates based on the field survey and pilot plant study have been prepared for all three dechlorination processes. The sulfur dioxide process seems to be the most cost-effective method for dechlorination.

This report was submitted by the Sanitation Districts of Los Angeles County, Whittier, California, in fulfillment of Contract Nos. 14-12-150 and 68-03-2745 under the partial sponsorship of the U.S. Environmental Protection Agency. This report covers the period from June 1973 to September 1979, and work was completed as of January 1980.

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ACKNOWLEDGMENTS

This study was undertaken through a cooperative effort of the U.S. Environmental Protection Agency and the Sanitation Districts of Los Angeles County. The pilot plant study was performed at the Sanitation Districts' Advanced Wastewater Treatment Research Facility, Pomona, California..

The cooperation of various treatment plant personnel involved in field visits and the mail questionnaire survey is greatly appreciated.

Mr. George C. White gave invaluable assistance in the field survey.

Credits for this research project are extended to staff of the Pomona Research Laboratory and the San Jose Creek Microbiology Laboratory, both of the Sanitation Districts.

Special thanks are also expressed to Ms. Vicki Rice and Mr. John Cussen for their assistance in preparing this report.

SECTION 1

INTRODUCTION

Because of growing concern over the effects of chlorine and chloramines on the aquatic environment, dechlorination has become an important unit process to be considered as part of a wastewater treatment system employing chlorination as its disinfection process. The chlorine residuals, either free chlorine or chloramines have been well demonstrated to be toxic to fish and other aquatic organisms (1, 2, 3, 4). Therefore, the regulatory agencies have already or are in the process of establishing residual chlorine effluent standards for wastewater discharges (5, 6, 7). These established standards or proposed criteria for chlorine residuals are normally dictated by the residual chlorine detection limits.

The Sanitation Districts of Los Angeles County are required by the California Regional Water Quality Control Board (Los Angeles Region) to provide dechlorination facilities at their water reclamation plants for chlorine residual control. The total chlorine residuals allowed in these plant effluents, which are discharged into nearby creeks or rivers, are equal to or less than 0.1 mg/l. This study was initiated as a result of the need for dechlorination in the Sanitation Districts' facilities. The study had three main objectives as follows:

1. To establish on a pilot scale the utility and efficiency of sulfur dioxide (SO_2) for dechlorinating chlorinated secondary municipal wastewater effluent.

2. To demonstrate on a full scale the cost effectiveness of SO_2 dechlorination under actual operating conditions.

3. To examine and ascertain the cost effectiveness of other methods of dechlorination (i.e., activated carbon and holding tank processes).

The study objectives have been accomplished through three main phases of work: (1) a literature review, (2) pilot scale testing, and (3) full scale evaluation.

The literature review was performed with an extensive search on the practice of dechlorination in the United States and other countries, the assessment of the need for reaeration and pH adjustment in the dechlorinated effluent, and the extent of bacteriological "aftergrowth" in outfall pipelines and receiving waters.

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The pilot scale testing was conducted at the Sanitation Districts' Advanced Wastewater Treatment Research Facility, Pomona, California. The three methods of dechlorination evaluated were sulfur dioxide (SO_2), granular activated carbon, and water impoundment. Emphasis was placed on the sulfur dioxide process because of its potential for being the most cost effective method for dechlorination. The granular carbon method had been investigated previously at the same research facility, and the results are included in this report. The water impoundment method was evaluated concurrently with the sulfur dioxide method.

The full scale evaluation was conducted by means of a field survey of all California treatment plants that practiced dechlorination by any means. The primary objectives of the field survey were to assess the effectiveness and reliability of actual full scale dechlorination installations. Information on the methods of control for the sulfonation system, cost effectiveness, and the bacteriological aftergrowth in the dechlorinated effluent were also requested through the field survey, which was conducted with both questionnaire correspondence and site visit followup.

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SECTION 2

CONCLUSIONS

1. The sulfur dioxide process is considered to be the most cost effective method for dechlorination, particularly in the State of California.

2. The feed forward method of control, with flow as the primary signal and residual chlorine as the secondary signal, is most commonly used in sulfur dioxide dechlorination facilities.

3. Overdosing the chlorinated wastewater effluents with sulfur dioxide is essential to accomplish consistent dechlorination.

4. Excessive overdose of sulfur dioxide can be avoided by using discrete instruments and alternate methods of feed.

5. The reliability of the sulfur dioxide feed forward control system is generally good.

6. The residual chlorine analyzer is the weakest link in a sulfur dioxide feed system. Most analyzers manufactured today are not capable of maintaining accurate calibration in the absence of minimal amount of chlorine.

7. No significant physical-chemical degradation of the effluent was found after dechlorination with sulfur dioxide. Depletion of dissolved oxygen or reduction in pH was not observed in the pilot plant studies at a sulfur dioxide to residual chlorine dosage ratio of 2 to 1.

8. Bacteriological aftergrowth in some microorganism populations was found after dechlorination. This was observed predominantly in the total coliform group. Some increases in fecal coliforms and other bacteria (as detected in the total plate count) were also found in the dechlorinated effluents. Salmonella was not detected in most of the samples. Fecal streptococci in the effluent remained relatively unchanged after dechlorination.

9. The bacterial increases in the dechlorinated effluents seem to be attributed to contamination by the microorganism communities existing in the dechlorinated effluent rather than reactivation of injured bacterial cells.

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10. Similar effects on the chemical, physical and bacteriological qualities of the dechlorinated effluents were found for the carbon adsorption and holding tank dechlorination processes as with the sulfur dioxide dechlorination process.

11. The carbon adsorption dechlorination process is substantially more expensive than the other two processes investigated. It is not economically feasible to use the carbon adsorption process solely for dechlorination purpose.

12. The holding pond process may become more cost-effective than the sulfur dioxide process for dechlorination where inexpensive land is available and simpler pond construction is acceptable.

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SECTION 3

RECOMMENDATIONS

1. More reliable chlorine analyzer should be developed to perfect the automation of the sulfur dioxide feed control system.
2. The effects of organic loading on the carbon capacity for dechlorination should be thoroughly evaluated.

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SECTION 4

LITERATURE REVIEW

GENERAL

As part of this wastewater dechlorination study, a literature review has been conducted to address the following subjects:

1. The practice of dechlorination with respect to types of processes and their control and monitoring instrumentation.
2. An assessment of the extent to which reaeration and pH adjustment is necessary following dechlorination, particularly, the sulfur dioxide dechlorination.
3. The extent of bacteriological aftergrowth in outfall pipelines and receiving waters.

Dechlorination has been practiced for quite some time in the field of water treatment(8,9). The practice is usually associated with a superchlorination for destruction of odors, tastes and other chlorine demand causing substances in addition to bacteria and viruses(10). The excess chlorine residuals are first removed by dechlorination process from the superchlorinated effluents, and appropriate amounts of chlorine are then added into the dechlorinated effluents to maintain desirable levels of chlorine residuals in the final effluents. Such practice has been found to be satisfactory for maintaining a necessary level of chlorine residual to provide bacteriologically safe water.

The application of dechlorination to wastewater treatment is rather a new practice in the field. It has been employed recently to protect aquatic life from the toxicity of the chlorine residuals in the discharging effluents. Therefore, the sources of information regarding this practice are very limited. Nevertheless, this section is intended to summarize these pertinent information in both fields of water and wastewater treatment.

DECHLORINATION STANDARDS

Chlorination has been commonly employed to achieve various disinfection standards for wastewaters discharging into natural water streams or lakes. These disinfection standards usually require certain levels of chlorine

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residuals to ensure the necessary destruction of bacteria and viruses. The remaining chlorine residuals have been found to be toxic to aquatic life, especially fish(3,4,11,12).

Depending on the type of chlorine discharge (i.e., continuous or intermittent), the toxicity limits of total chlorine residuals for the protection of various aquatic species may vary widely, from less than 0.002 mg/l for continuous discharge to 0.4 mg/l for intermittent discharge, as proposed by Brungs(3), and Basch and Truchan(11).

Having recognized the problem of residual chlorine, the regulatory agencies have already or are in the process of establishing residual chlorine standards for wastewater discharges. For example, the State of Maryland has set 0.02 and 0.5 mg/l total chlorine residual standards, respectively, for trout and other waters(6); the State of California has set slightly different chlorine residual limits, mostly at the levels of 0.1 mg/l or less, for waste water discharges into different receiving water systems within each individual basin under Regional Water Quality Control Board.

Any standards with total chlorine residuals less than 0.05 mg/l are essentially requiring that no chlorine residuals should be detectable in the discharged effluents. This is based on the current capabilities of instrumentation and analytical procedures for detecting the chlorine residuals

DECHLORINATION PROCESSES

There are basically three types of dechlorination processes in the field of practice. They are:

1. Dechlorination with chemical solutions.

    (a) Sulfur compounds, such as sulfur dioxide, sodium sulfite, sodium bisulfite and sodium thiosulfate.
    (b) Hydrogen peroxide.
    (c) Ammonia.

2. Dechlorination with granular activated carbon.

3. Dechlorination by dissipation in holding lagoons.

Among the above processes, the sulfur dioxide dechlorination process seems to be the most popular one because of its low cost and its readily available supply.

Dechlorination with Sulfur Compounds

Sulfur Dioxide--

The various chemical reactions involved in sulfur dioxide dechlorination process are shown as follows:

$$SO_2 + H_2O \longrightarrow H_2SO_3$$

$$HOCl + H_2SO_3 \longrightarrow HCl + H_2SO_4$$

$$NH_2Cl + H_2SO_3 + H_2O \longrightarrow NH_4Cl + H_2SO_4$$

$$NHCl_2 + 2H_2SO_3 + 2H_2O \longrightarrow NH_4Cl + HCl + 2H_2SO_4$$

$$NCl_3 + 3H_2SO_3 + 3H_2O \longrightarrow NH_4Cl + 2HCl + 3H_2SO_4$$

The above equations indicate that acids are produced during the sulfur dioxide dechlorination reactions. These acids may cause substantial pH reduction in low alkalinity waters and make it necessary to adjust pH after dechlorination. The equations also show that both free chlorine and chloramines can be dechlorinated with sulfur dioxide.

Usually a slight excess amount of sulfur dioxide is added to ensure the complete removal of the chlorine residual. However, the excess amount of sulfur dioxide may exist in the water as sulfite ($SO_3^=$) or react with the dissolved oxygen in the water as indicated by the following reactions:

$$SO_2 + H_2O \longrightarrow H_2SO_3$$

$$2SO_2 + 2H_2O + O_2 \longrightarrow 2H_2SO_4$$

Excessive sulfite (i.e., >10 mg/l) has been reported to be partially responsible for the mortality of some fish species(4). The excess sulfite will cause the depletion of dissolved oxygen in the receiving streams, which may endanger the aquatic lives. The reaction of excessive sulfur dioxide with water may also cause further pH reduction in the dechlorinated water.

The reaction between sulfur dioxide and chlorine residual is instantaneous(13). Therefore, a contact tank other than the initial sulfur dioxide mixing and sparging compartment is usually not needed for a sulfur dioxide dechlorination system.

Other Sulfur Compounds --

Similar reactions can readily occur between other sulfur compounds, such as sodium sulfite, sodium bisulfite and sodium thiosulfate, and residual chlorine to produce essentially the same end products as those of sulfur dioxide dechlorination. Sodium thiosulfate is not commonly used as a dechlorinating agent because of its relatively slower reaction and the reported odor nuisance associated with its reaction(13).

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Dechlorination with Hydrogen Peroxide

The use of hydrogen peroxide (H_2O_2) as a dechlorinating agent is not well documented. The chemical is believed to react with free residual chlorine only and not with residual chloramines. The reaction is as follows:

$$HOCl + H_2O_2 \longrightarrow HCl + H_2O + O_2$$

Because of the production of oxygen in its reaction, it is possible that a closed loop control on the basis of dissolved oxygen can be used to adjust the feed of hydrogen peroxide in the dechlorination operation. Furthermore, no additonal pollutants may result from the overdosing of hydrogen peroxide.

Dechlorination with Ammonia

The residual free chlorine can be effectively removed by ammonia according to the following reaction:

$$3Cl_2 + 2NH_3 \longrightarrow N_2(gas) + 6HCL$$

The stoichiometric relationship is 6.3 mg chlorine to 1 mg ammonia. The field practice indicated that 0.17 mg/l of NH_3 could dechlorinate 1 mg/l of HOCl(14). This low NH_3 dosage requirement is considered to be the chief benefit of using ammonia for dechlorination. However, the reaction time required to complete the ammonia dechlorination is rather lengthy with a minimum of 20 minutes(15). Furthermore, it is extremely difficult to hit exactly the proper location on the breakpoint curve to produce the above reaction for complete removal of free chlorine residual. Usually, the resulting residuals may be a mixture of monochloramine and dichloramine.

Dechlorination with Granular Activated Carbon

Use of granular activated carbon as a means for dechlorination following superchlorination in a municipal water treatment plant was practiced as early as 1910 in Reading, England(9). However, this kind of practice is considered to be too expensive for municipal operations, and thus its application has been limited to special water treatment problems.

Cassel et al.(16) reported that the activated carbon dechlorination process could effectively remove the soluble organics, free chlorine residuals and chlorinated organics from the effluents treated with breakpoint chlorination for ammonia removal. Bauer and Snoeyink(17) also employed activated carbon for removing ammonia after being chlorinated with dosages less than the requirement of a breakpoint chlorination.

The reaction equations proposed for the various activated carbon dechlorination applications may be summarized in the following:

$$\underline{C} + HOCl \longrightarrow \underline{CO} + HCl$$

where $\underline{C}$ represents the clean state activated carbon and $\underline{CO}$ represents the oxidized state activated carbon. Some of the surface oxides may decompose to CO or CO_2.

According to Bauer and Snoeyink(17), dichloramine may react with activated carbon and be converted to nitrogen gas and hydrochloric acid as follows:

$$2NHCl_2 + H_2O + \underline{C} \longrightarrow N_2 \text{ (gas)} + 4HCl + \underline{CO}$$

The above reaction is believed to occur much more rapidly than the following reactions of monochloramine with activated carbon and no evidence of reconversion to NH_3 has been obtained.

$$NH_2Cl + H_2O + \underline{C} \longrightarrow NH_3 + HCl + CO$$

$$2NH_2Cl + \underline{CO} \longrightarrow N_2\text{(gas)} + 2HCl + C$$

The acid produced by the above reactions may necessitate a pH adjustment step after dechlorination, as in the case with sulfur compounds.

According to the above reactions, activated carbon dechlorination can be employed to produce any desired degree of ammonia removal in addition to dechlorinating the water. This dual removal function is important for protecting aquatic life from the toxicity of ammonia and chlorine residual. However, the dual function can be accomplished only with proper pH control to ensure the predominant form of chloramine is dichloramine. This is further supported by the results obtained by Atkins et al.(18) in their pilot plant studies at Owasso, Michigan.

The oxidation of the activated carbon surface by the chlorine residuals during dechlorination may reduce the carbon adsorption capacity for aromatic compounds (19,20). The reduction may be attributed to the decrease of surface area and the increase in surface acidity. Although Magee(21) reported that some surface oxides may be decomposed, as indicated above, to CO and CO_2, the carbon surface eventually becomes saturated with oxides. It is not known if the buildup of oxides may result in the decrease of dechlorination efficiency.

It has been shown that the carbon adsorption capacity for dechlorination can be effectively restored with thermal regeneration processes(21,22).

Dechlorination with Holding Lagoons

The technical information regarding chlorine dissipation in holding lagoons is not well documented. The scarcely available data were mostly developed from laboratory or small scale pilot plant observations.

Snoeyink and Markus(23) found that free chlorine in a secondary effluent exposed to bright sunlight decayed from 2.0 to 0.2 mg/l in approximately 30 minutes, while monochloramine decayed far more slowly. Katz(24) demonstrated in his laboratory studies that the rates of chlorine dissipation can be altered by the presence of nitrogenous compounds, sunlight and high salinity.

DECHLORINATION INSTRUMENTATION

Depending on types of processes being employed for dechlorination, the process control instrumentation may range from a simple effluent chlorine residual monitoring system to a more sophisticated combination system consisting of a dechlorinating chemical and a chlorine residual monitor. The latter system is usually required for a dechlorination process with chemical solutions, such as sulfur dioxide and sodium sulfite.

Since current residual chlorine standards are beyond the control abilities of commercially available chlorine residual analyzers, an improvement of the accuracy, sensitivity and reliability of the chlorine residual analyzer is vital to effective dechlorination process control for aquatic life protection.

A feed forward control mode, using a flow signal and a predechlorination chlorine residual signal, is presently considered as the most practical control mechanism for sulfur dioxide dechlorination. However, the actual chlorine residual in the dechlorinated effluent is not automatically recorded in a feed forward control system. A feedback system can be used to control the effluent residual chlorine only if a reliable, sensitive and accurate chlorine residual analyzer for measuring trace amounts of chlorine is available.

DECHLORINATION EXPERIENCE

pH Adjustment

According to the various chemical reactions described previously, the dechlorination processes usually result in the production of acids in the dechlorinated effluent, i.e., hydrochloric and/or sulfuric acid. The extent of the pH effects of these acids on the effluents depends greatly on the buffer capacities of the dechlorinated waters.

The alkalinity of chlorinated wastewater effluents is normally in the range of 150 to 200 mg/l as $CaCO_3$. This range of alkalinity provides a moderate level of buffer capacity for maintaining an acceptable pH in the dechlorinated effluent. Therefore, there is usually no need for pH adjustment for a well operated dechlorination plant.

Post-Aeration

The potential of dissolved oxygen depletion associated with dechlorination processes may be attributed to the following factors:

1. The oxidation of excess dechlorinating chemicals by the dissolved oxygen, as the oxidation of residual sulfite in the sulfur dioxide dechlorination system.

2. The consumption of dissolved oxygen by the biological oxidations taking place in the dechlorination systems, such as in the case of activated carbon dechlorination.

Consequently, the need for post aeration after dechlorination is dependent on the following parameters:

1. The concentration of dissolved oxygen in the water stream ahead of the dechlorination system.

2. The amount of excess dechlorinating chemicals in the dechlorinated effluent.

3. The potential of biological growth in the dechlorination system.

Under normal operating conditions, the sparging and rapid mixing chamber in a sulfur dioxide dechlorination system is able to provide adequate dissolved oxygen to compensate for the oxygen depletion caused by the oxidation of the limited amount of excess sulfite in the dechlorinated effluent. Therefore, post-aeration is not normally needed with a well-designed mixing system.

Bacteriological Aftergrowth

The bacteriological aftergrowth is defined in this study as the rapid increase of bacterial population in the disinfected wastewater immediately following the removal of bactericidal effects. The remaining nutrients and organics in the biologically oxidized and disinfected wastewaters are generally believed to be adequate for sustaining bacteriological growth after the removal of bactericidal effects. Therefore, a rapid increase of bacterial population can be developed in the wastewaters by the following mechanisms.

1. Contamination

Gan (25) had observed an increase of total coliforms from a level of 2.2 MPN or less per 100 ml of sample to a level of approximately 1,000 MPN or more per 100 ml of sample in his carbon-dechlorination pilot plant studies. Since the residual chlorine could be effectively removed by the top layer of the granular activated carbon bed in the carbon-dechlorination system, the carbon bed below the active dechlorination layer would become an excellent environment for bacteriological growth. Such growth area is thus believed to be a natural source of bacterial contamination for dechlorinated wastewaters.

Slime build-up in outfall channels or conduits immediately following the dechlorination plants may be also responsible for the bacteriological aftergrowth in the dechlorinated wastewaters.

2. Photoreactivation

Scheible et al (26) had noted a 0.6 to 1.0 order of magnitude increase in fecal coliform levels after exposure of ultraviolet light irradiated samples to visible light. Such aftergrowth is believed to be caused by cell repair as a result of photoreactivation.

3. Loss of Harboring or Sheltering Effects

The crustacea or the suspended solids in the wastewaters may harbor or shelter the bacteria during the disinfection process and prevent them from being destroyed by the bactericidal effects. Tracy et al (27) believed that the harbored coliform bacteria could be released into the disinfected water after the damage of the crustacea and the removal of the residual chlorine. Similar effects are expected from the suspended solids.

Other types of bacteriological aftergrowth have also been observed by many investigators (28, 29, 30) down stream from effluent discharges or storm overflows. These types of aftergrowth are primarily attributed to the changes in nutrient levels and in the balances between bacteria and bacteria predators. The toxic bacterial metabolic products may play a role similar to that of the predators.

SECTION 5

FIELD SURVEY

GENERAL

An extensive survey of all treatment plants in the State of California practicing dechlorination was conducted during the study period. The dechlorination requirement for wastewaters in the State varies from one region to another. There are nine Regional Water Quality Control Boards in the State as indicated in Figure 1. Each Board sets and enforces the water quality requirements for the region under its jurisdiction. The chlorine discharge limits are set primarily according to the existing qualities and beneficial uses of the receiving waters.

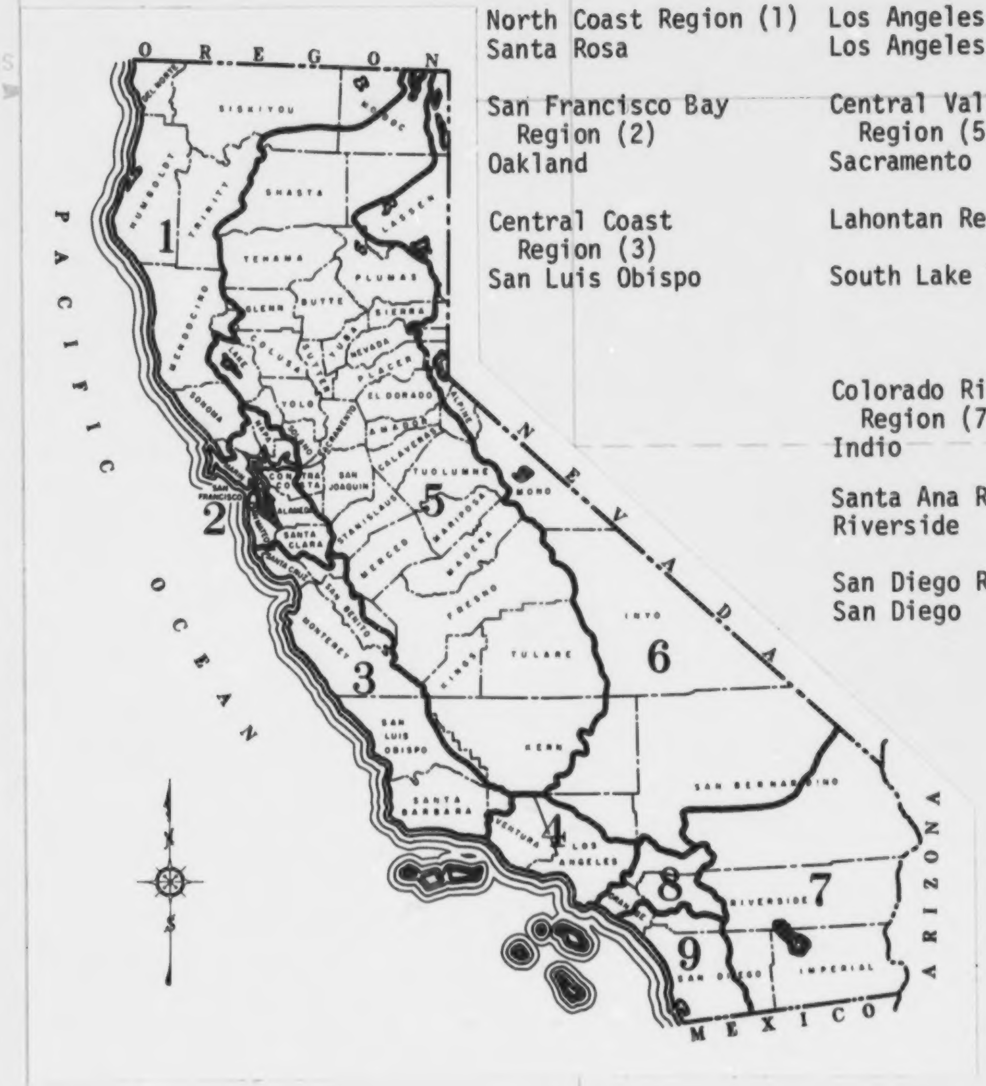
Dechlorination is employed mostly in the urban areas, such as San Francisco (Region 2), Sacramento (Region 5), and Los Angeles (Region 4). The threat to fish and wildlife is most prevalent in these areas because of the voluminous amount of wastewater discharges. Receiving streams and rivers are incapable of assimilating the chlorine discharge from the treatment plants without endangering fish lives and other aquatic organisms.

Region 2 dechlorinates approximately 3×10^6 m^3 (800 million gallons) of wastewater daily to protect the fish and wildlife habitat in the San Francisco Bay estuaries. The Bay is one of the most important coastal estuaries in the State. Myriads of fish and wildlife species utilize the Bay habitats for feeding and nursery ground. The Bay also functions as the major drainage outlet for wastewaters in the region. Dechlorination is thus necessary for wastewater discharges in the Bay.

Region 5 dechlorinates its wastewaters to protect the fish and waterfowl habitat in the rivers. Region 4 dechlorinates only the wastewater discharges from its inland plants to protect the fish in the low flowing rivers.

The North Coast (Region 1) had only three facilities dechlorinating their effluents during the field survey. However, rapid growth in the region has generated sufficient chlorinated wastewater to threaten the fish life in the area.

The Central Coast (Region 3) and San Diego (Region 9) regions utilized submarine ocean outfall to disperse their wastewater discharges. Therefore, no dechlorination was practiced in these areas.


OREGON
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CONTRA COSTA
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SAN JOAQUIN
CALAVERAS
TUOLUMNE
MONO
SANTA CLARA
STANISLAUS
MARIPOSA
MERCED
MADERA
SANTA CRUZ
SAN BENITO
FRESNO
INYO
MONTEREY
KINGS
TULARE
SAN LUIS OBISPO
KERN
SANTA BARBARA
SAN BERNARDINO
VENTURA
LOS ANGELES
ORANGE
RIVERSIDE
SAN DIEGO
IMPERIAL

North Coast Region (1)
Santa Rosa

San Francisco Bay Region (2)
Oakland

Central Coast Region (3)
San Luis Obispo

Los Angeles Region(4)
Los Angeles

Central Valley Region (5)
Sacramento

Lahontan Region (6)
South Lake Tahoe

Colorado River Basin Region (7)
Indio

Santa Ana Region (8)
Riverside

San Diego Region (9)
San Diego

Figure 1. Map of California Regional Water Quality Control Boards

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The Colorado River Basin (Region 7) and Santa Ana (Region 8) are water scarce regions. Wastewater effluents are normally discharged into ephemeral streams which contained virtually no fish life. Consequently, no dechlorination is required in these regions.

The Lahontan Region (Region 6) disposes its wastewater via land disposal and, therefore, has no dechloriantion facility.

The various Caifornia Regional Water Quality Control Boards were contacted in May 1977 for information regarding the dechlorinatin installations in their specific regions. From the list of treatment plants provided by the Boards, superintendents of the treatment plants were contacted by telephone in early June 1977 to inquire if dechlorination was practiced at their plants. A total of 35 plants out of the 55 facilities contacted already used sulfur dioxide dechlorination in their plants. The remaining 20 plants were divided into three different situations: (1) five plants were under construction; (2) five plants were still in design stages; and (3) ten plants used holding lagoons or long pipe lines as interim means for dechlorination.

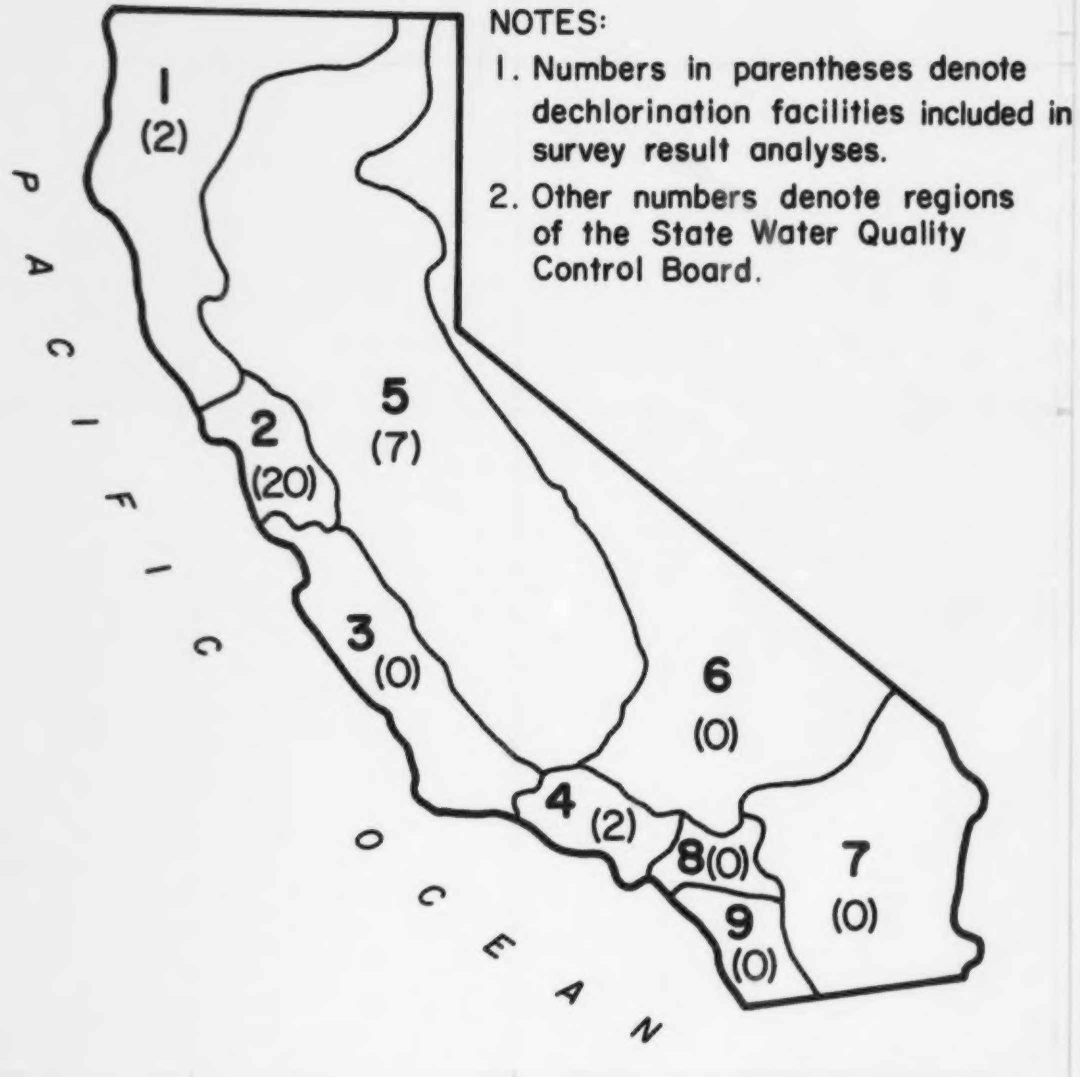
The survey-questionnaires were mailed to all 55 treatment plants in June 1977 and requests were made to return the completed questionnaires to the Sanitation Districts of Los Angeles County by the end of July 1977. However, only 31 of the 35 plants practicing sulfur dioxide dechlorination had returned their completed questionnaires in time for statistical analyses. The distribution of these 31 dechlorination facilities is shown in Figure 2.

QUESTIONNAIRE RESPONSES

A copy of the blank survey-questionnaire which covers general, engineering design and operational information inquiries is included in Appendix A of this report for reference. Responses to the questionnaires from the 31 dechlorination facilities are summarized in Tables 1, 2, and 3 with respect to three different categories of information. These results are expressed in terms of percent of total responses.

As indicated in Table 1, about 61 percent of the dechlorination facilities in the State of California had their initial startup operation in January, 1976 or later. This was about the time when the stringent water quality requirements were imposed on wastewater treatment facilities in California. The table also indicates that about 84 percent of the treatment plants employed secondary treatment processes ahead of their dechlorination facilities. The remaining plants either had primary or tertiary treatment processes as pretreatment units for dechlorination. Furthermore, the table indicates that 68 percent of the sulfur dioxide dechlorination facilities surveyed had an average flow of 2.3×10^4 m^3/day (6 mgd) or less.

The total chlorine residuals before dechlorination were in the range of 2 to 10 mg/l. These levels of chlorine residuals were required for



NOTES:

1. Numbers in parentheses denote dechlorination facilities included in survey result analyses.
2. Other numbers denote regions of the State Water Quality Control Board.

Figure 2. Distribution of dechlorination facilities included in survey results analyses.

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TABLE 1. PROFILE OF DECHLORINATION FACILITIES IN SURVEY (1977)

Description	Percent of total responses
(a) Startup date of dechlorination facilities	
Before January 1976	39
After January 1976	61
(b) Type of treatment preceding dechlorination	
Primary	10
Secondary	84
Tertiary	6
(c) Average daily plant flow	
Less than $2.3\text{x}10^4 m^3/d$ (6 mgd)	68
$2.3\text{x}10^4$ to $3.8\text{x}10^4 m^3/d$ (6-10 mgd)	16
Greater than $3.8\text{x}10^4 m^3/d$ (10 mgd)	16
(d) Sulfur dioxide capacity	
0 to 45.4 kg/d (0 to 100 lbs/day)	13
45.8 to 227 kg/d (101 to 500 lbs/day)	35
Greater than 227 kg/d (500 lbs/day)	52
(e) Total coliform discharge standard	
Less than or equal to 2.2/100 ml	22
Less than or equal to 23/100 ml	16
Less than or equal to 100/100 ml	10
Less than or equal to 240/100 ml	42
Others	10
(f) Total residual chlorine discharge standard	
0	58
Less than or equal to 0.1 mg/l	29
Greater than 2 mg/l	13

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TABLE 2. ENGINEERING DESIGN INFORMATION OF DECHLORINATION FACILITIES IN SURVEY (1977)

Description	Percent of total responses
(a) Type of feed control system	
Feedforward	87
Feedback	10
Feedforward and feedback	3
Flow paced	27
Residual control	27
Flow and residual controls	46
Pneumatic flow signal	7
Electronic flow signal	93
Pneumatic dosage signal	10
Electronic dosage signal	90
Gap residual controller	16
Proportional and reset controller	26
None	58
Multiplier	35
Without multiplier	65
With adjustable slope factor	10
Without adjustable slope factor	90
(b) Contacting method	
SO_2 injected in mixing chamber	32
SO_2 injected in outfall pipe	68
Reaeration provided after dechlorination	3
Reaeration not necessary after dechlorination	97
pH adjustment provided after dechlorination	3
Others	97

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TABLE 3. OPERATIONAL INFORMATION OF DECHLORINATION FACILITIES IN SURVEY (1977)

Description	Percent of total responses
(a) Is dechlorination system operated 24-hrs daily?	
Yes	94
No	6
(b) What is the desirable SO_2 : Cl_2 ratio employed?	
1 or less	74
Greater than 1	26
(c) Is overdosing necessary to meet standard?	
Yes	87
No	13
(d) Is SO_2 feed control system reliable?	
Yes	58
No	42
(e) Will system handle drastic fluctuation of residual chlorine?	
Yes	50
No	50
(f) Is biological aftergrowth observed after dechlorination?	
Yes	6
No	94

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meeting the various disinfection goals shown in Table 1. The disinfection requirement of most wastewater treatment facilities was to meet either a 2.2 or less total coliform MPN per 100 ml or 240 or less total coliform MPN per 100 ml. The limit of 2.2 or less MPN/100 ml was required for facilities which discharged their effluents into water streams for non-restricted recreation usage, while the limit of 240 or less MPN/100 ml was for facilities which discharged their effluents into shellfish harvesting areas.

The limits of chlorine residuals for most wastewater discharges were generally 0.1 mg/l or less. Several dechlorination facilities reported total chlorine residuals of 2 to 6 mg/l in their dechlorinated effluents. In these facilities, the discharge requirement for chlorine was not monitored until several kilometers downstream. Consequently, the plant can discharge a higher level of chlorine residual at the plant site. Due to normal chlorine dissipation along the channel, virtually all the chlorine residuals were found to be reduced by the time they reached the required monitoring point.

Table 2 summarizes the engineering design information gathered in the field survey. Most responses to the survey-questionnaires showed that a feed-forward type, with primary control based on flow and secondary control based on chlorine residual levels at the chlorine contact chamber effluent, was a preferred control system for SO_2 feed. The secondary control signal on chlorine residuals must be fed forward instead of being fed backward, since currently available residual chlorine analyzers are not capable of monitoring and controlling the trace amount of chlorine residual in the dechlorination effluent. The analyzers will lose their sensitivities and accuracies after extended periods of measuring trace or zero amount of chlorine residuals. The survey results also indicate that both the flow and dose signals are transmitted electronically rather than pneumatically, thus reflecting the modernization of the control equipment. However, controllers, multipliers, and adjustable slope factors are not used in most installations. These devices have been used to fine-tune the sulfur dioxide requirement for dechlorination.

The survey results on the operational information of the dechlorination facilities are summarized in Table 3. Approximately 94 percent of the facilities surveyed operated their dechlorination systems continuously on a 24 hour basis. The remaining 6 percent operated their systems intermittently, turning on the sulfonators only at high chlorine residual levels. Seventy-four percent of the facilities surveyed attempted to operate their dechlorination systems with the theoretical sulfur dioxide/chlorine residual ratio of 0.9. However, most (87 percent) found it necessary to overdose sulfur dioxide in order to achieve the stringent chlorine residual standard. Approximately 97 percent of the dechlorination facilities surveyed reported that it was not necessary to adjust pH and perform reaeration of their dechlorinated effluents. Biological aftergrowth was not observed in 94 percent of the dechlorination plant effluents. Only about 68 percent of the correspondents of dechlorination facilities believed that their SO_2 feed control systems were reliable.

SITE VISITS

Of the 55 dechlorination facilities surveyed, 17 plants were selected for site visits to obtain further information regarding the operation of dechlorination systems. These plants, as listed in Table 4, are generally located in the San Francisco, Sacramento, San Jose, Santa Rosa, and Los Angeles areas of the State of California. The specific objectives of the site visits were to study various SO_2 feed control methods and interview plant operators regarding operations of their systems. All the treatment facilities visited were secondary treatment systems. The plant flow capacities ranged from 1.1×10^4 to 3.0×10^5 m^3/day (3 to 80 mgd). The sulfonator capacities ranged from 200 to 6,900 kg/day (450 to 15,200 lb/day).

The most common layout of sulfur dioxide dechlorination system employed in the plants visited is shown in Figure 3. As indicated in the figure, a feed forward residual signal and a feed forward flow signal were fed to the sulfonator. These two signals were sometimes combined into a product signal through an electronic multiplier before feeding to the sulfonator. This was done to avoid having to excessively overdose the chlorinated effluent with SO_2.

In order to improve the control system further, an electronic ratio controller was adopted after the multiplier in some facilities. The ratio station maintained the desired ratio between the flow and residual signals combined in the multiplier. This seemed to provide a more precise control on the sulfur dioxide dosage requirement for dechlorination.

Two alternate methods have been devised to overcome the inability of the chlorine analyzer in providing a feedback signal to the sulfonator. Figure 4 shows a schematic of such a system.

In alternate No. 1, a two-stage method of dechlorination is used. One chlorine analyzer is used to instruct sulfonator No. 1 to dechlorinate to a 10:1 ratio of the chlorine residual discharge limit. The analyzer seems to perform best within a 10 to 1 setting. Calibration is maintained very well because of the continuous presence of chlorine residual in the first-stage dechlorinated effluent. Sulfonator No. 2 is then used to remove the remaining residual chlorine. Because the residual chlorine has been reduced to approximately 1 mg/l level in the first-stage dechlorinated effluent, excessive overdose of the sulfur dioxide with sulfonator No. 2 is thus avoided.

In alternate No. 2, a biased residual chlorine signal is transmitted through the analyzer to keep it in calibration. A feedback residual signal from the dechlorinated effluent greater than the biased signal signifies incomplete dechlorination. The sulfur dioxide is programmed to dose proportional to any signal greater than the biased signal.

The simple feed forward sulfur dioxide feed control system is inadequate for most dechlorination installations. It requires a small

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TABLE 4. DECHLORINATION FACILITIES VISITED IN SURVEY (1978)

Dechlorination facilities	Operated By	SO_2 Capacity kg/day	Daily avg. flow m^3/d
City Main WTP	City of Sacramento	6,900	1.8×10^5
San Jose/Santa Clara WPCP	City of San Jose	3,450	3.0×10^5
Northeast WRP	County of Sacramento	2,724	5.0×10^4
Arden WTP	County of Sacramento	1,725	1.9×10^4
San Pablo San. WPCP	San Pablo San. Dist.	908	3.0×10^4
Main Treatment Plant	San Rafael San. Dist.	908	1.1×10^4
Hayward WTP	City of Hayward	908	4.5×10^4
Pomona WRP	L.A. Co. San. Dist.	908	2.3×10^3
Harold May WQCP	City of Palo Alto	863	1.1×10^5
Laguna WTP	City of Santa Rosa	454	1.1×10^4
Valencia WRP	L.A. Co. San. Dist.	454	1.1×10^4
Cordova WTP	County of Sacramento	431	7.6×10^3
Richmond WPCP	City of Richmond	409	2.7×10^4
Irvington WTP	Union Sanitary Dist.	227	2.3×10^4
Newark WTP	Union Sanitary Dist.	227	1.9×10^4
Alvarado WTP	Union Sanitary Dist.	227	1.1×10^4
West College WTP	City of Santa Rosa	204	1.5×10^4

Notes: 1 kg/day = 2.2 lbs/day; 1 $m^3/d = 2.64\times10^{-4}$ mgd

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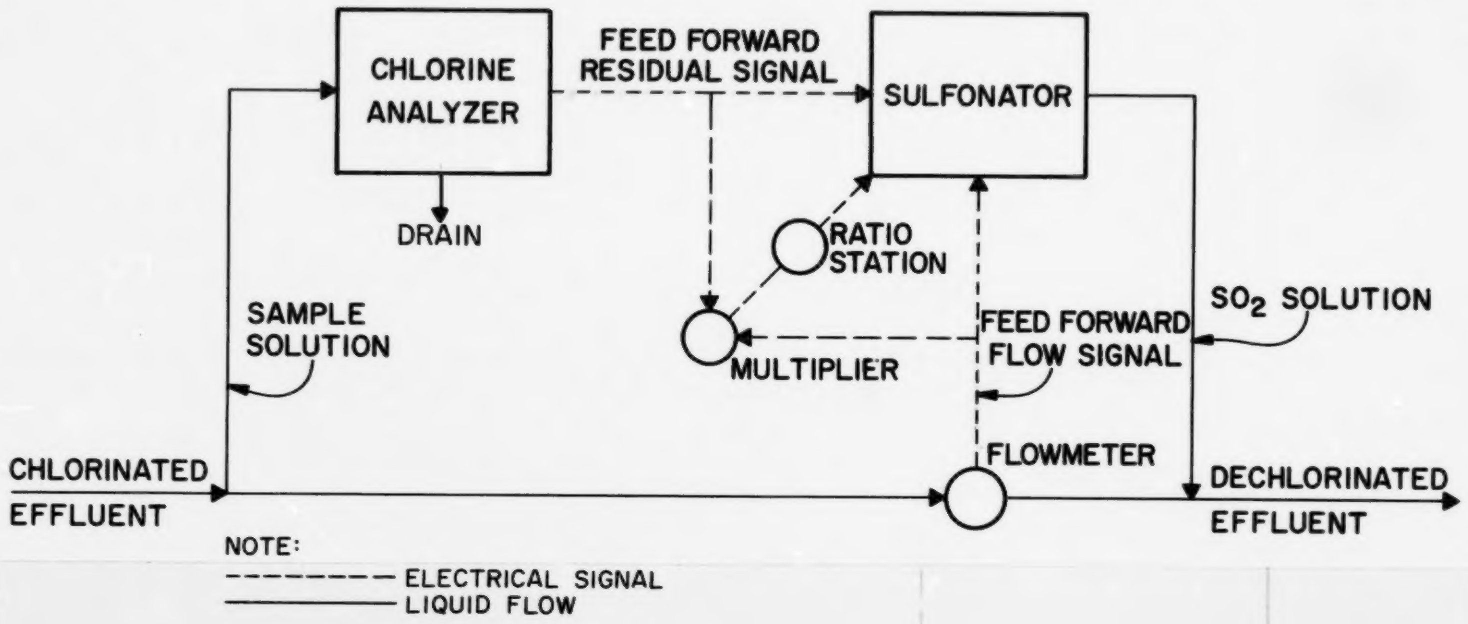
CHLORINE ANALYZER
FEED FORWARD RESIDUAL SIGNAL
SULFONATOR
DRAIN
RATIO STATION
SAMPLE SOLUTION
MULTIPLIER
FEED FORWARD FLOW SIGNAL
SO2 SOLUTION
FLOWMETER
CHLORINATED EFFLUENT
DECHLORINATED EFFLUENT
NOTE:
ELECTRICAL SIGNAL
LIQUID FLOW

Figure 3. Feed control system most commonly employed in sulfur dioxide dechlorination facilities in California.

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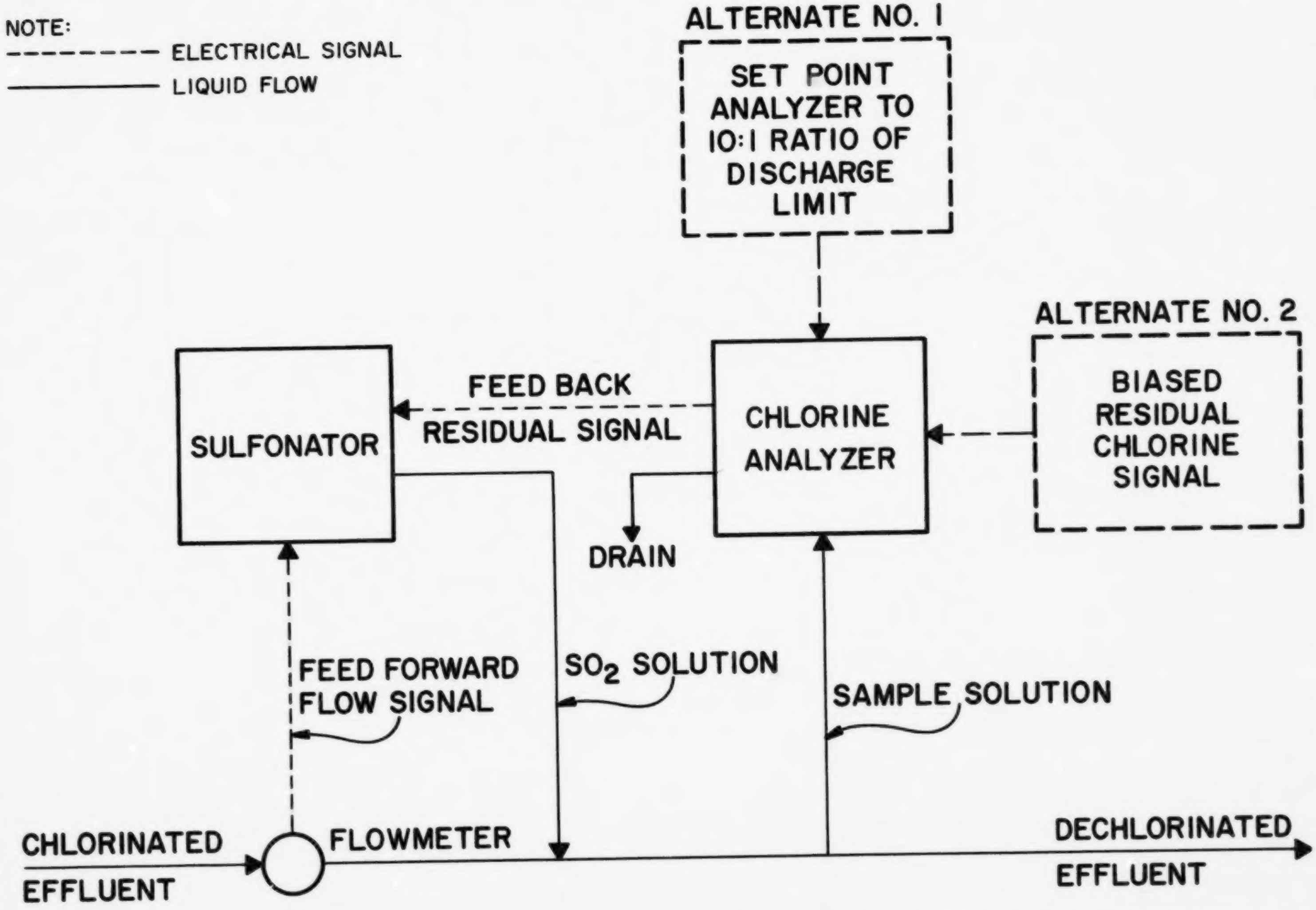
NOTE:
-------- ELECTRICAL SIGNAL
——— LIQUID FLOW
ALTERNATE NO. 1
SET POINT ANALYZER TO 10:1 RATIO OF DISCHARGE LIMIT
ALTERNATE NO. 2
BIASED RESIDUAL CHLORINE SIGNAL
SULFONATOR
FEED BACK RESIDUAL SIGNAL
CHLORINE ANALYZER
DRAIN
FEED FORWARD FLOW SIGNAL
SO2 SOLUTION
SAMPLE SOLUTION
CHLORINATED EFFLUENT
FLOWMETER
DECHLORINATED EFFLUENT

Figure 4. Feed control systems used in dechlorination facilities to avoid excessive SO_2 overdose.

capital investment and offers simplicity of control. However, the feed forward control system requires an overdosing of sulfur dioxide to accomplish the stringent dechlorination goals. Such an overdosing cost may become a significant factor in large dechlorination installations. Alternate sulfur dioxide control systems discussed previously seem to be more economical for large dechlorination installations. They reduce the sulfur dioxide overdose requirement and hence the operating chemical cost.

According to the field operators contacted, the weakest link in a sulfur dioxide feed control system was the chlorine residual analyzer. The measuring electrode of the chlorine analyzer lost its sensitivity rapidly in a dechlorination effluent. The presence of some amount of chlorine residual seemed to help prevent oxidation of the electrode. The abrasive grits in the measuring cell block were found not able to prevent oxides from forming on the electrode in the absence of chlorine residual.

Figure 5 shows a schematic of a residual chlorine sampling cell. Measuring of the chlorine residual takes place in the measuring cell block. The platinum is the reference electrode and the copper is the measuring electrode. A small D.C. current is produced in the presence of free chlorine or iodine proportional to its concentration. This current is measured by a recording ammeter in terms of mg/l of chlorine. The efficient operation of the analyzer is dependent upon several factors, all of which are equally important. The cell block and electrodes have to be free from biological or chemical fouling. Continuous mixing with abrasive grit or filtration have been successful to some extent in preventing contamination of the electrodes. The buffer solution must be maintained since the analyzer is calibrated to read accurately at a specific pH. The flow and pressure of the sample water must be fairly constant, since they affect cell current production. A malfunction in any of the above conditions will give a false reading and result in underdosing or overdosing of the sulfur dioxide.

During the site visit, it was learned that poor performance was experienced with the chlorine analyzer when the plant received a high proportion of industrial wastes. Plugging of the measuring cell block frequently occurred. Installation of filters preceding the cell block did not seem to improve the reliability of the chlorine analyzer. However, the operators of the sulfonation systems were generally satisfied with the reliability of their sulfonators. Most of the operators visited felt a slight overdose of the sulfur dioxide was necessary to meet the discharge requirement of 0.1 mg/l or less chlorine residual consistently.

Biological growth in the dechlorinated effluents was not visually observable in most plants since the effluents were usually discharged in a submerged outfall pipe or intermingled with the receiving waters containing natural fresh water slime growth. However, laboratory analytical results from these plants indicated an increase in total coliforms after dechlorination. As a result, coliform discharge limitations were usually exceeded at the point of discharge. The California Regional Water Quality Control

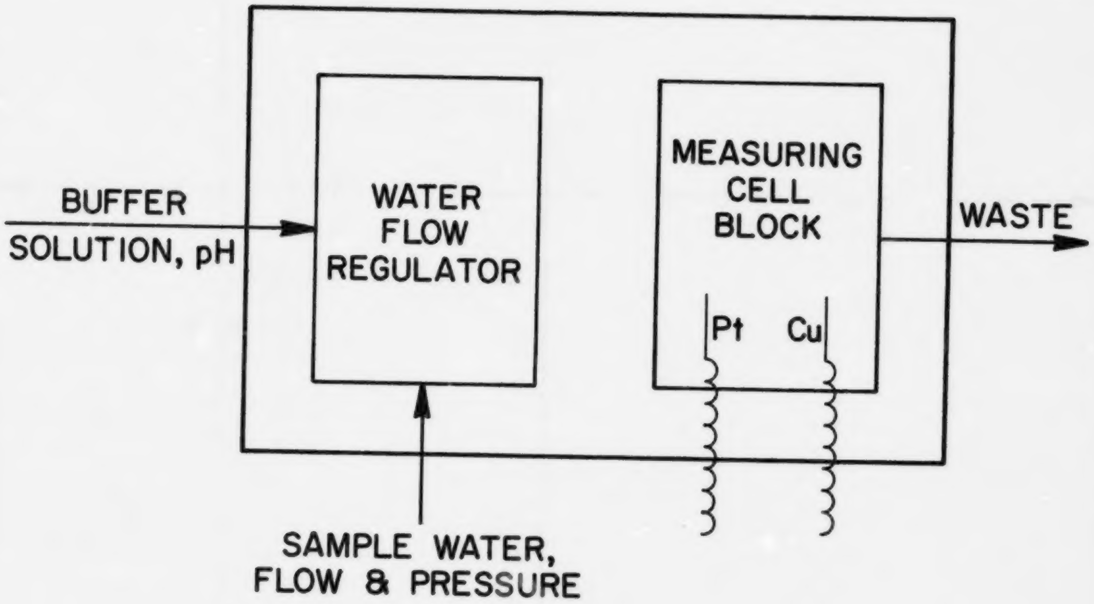
BUFFER
SOLUTION, pH
WATER
FLOW
REGULATOR
MEASURING
CELL
BLOCK
Pt
Cu
WASTE
SAMPLE WATER,
FLOW & PRESSURE

Figure 5. Critical components of a chlorine residual analyzer.

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Boards have allowed the treatment plants to monitor coliform results before dechlorination.

A continuous monitoring of the dechlorinated effluent was previously required in some cases for compliance with the discharge standards of California Regional Water Quality Control Boards. However, since a continuous recording of zero chlorine residual on the recorder chart is not possible because of the limitation of the chlorine analyzer, the California Regional Water Quality Control Baords have modified their requirements for monitoring of the dechlorinated effluents for chlorine residuals from a continuous basis to an hourly basis. The analyzer monitoring the chlorinated effluent is temporarily used to monitor the dechlorinated effluent for residual chlorine once every hour. Such a special arrangement can keep the chlorine analyzer in line with calibration.

SECTION 6

PILOT PLANT STUDIES

GENERAL

The dechlorination pilot plant studies were conducted at the Los Angeles County Sanitation Districts' Pomona Research Facility, Pomona, California. The systems investigated included sulfur dioxide, holding-tank impoundment, and activated carbon adsorption dechlorination processes. The pilot plant systems which are depicted schematically in Figure 6 were comparatively large scale ranging from 95 to 760 l/min (25 to 200 gpm) in flow rate.

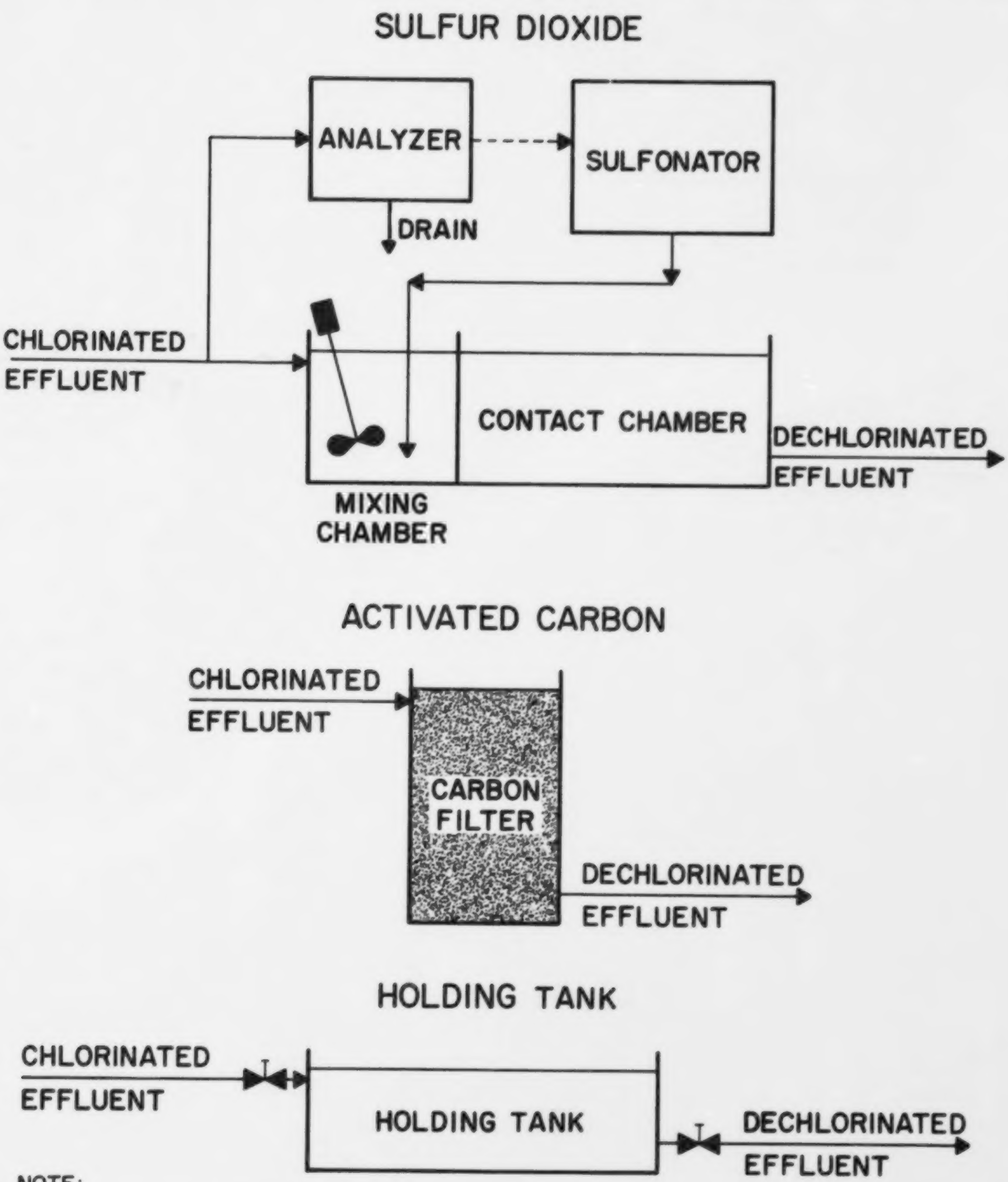
The unchlorinated secondary effluent water used in these pilot plant studies was obtained from the nearby Pomona Water Reclamation Plant, which is owned and operated by the Sanitation Districts. The Pomona Water Reclamation Plant consists of primary sedimentation, activated sludge biological oxidation, secondary sedimentation, granular activated carbon adsorption, chlorination, and sulfur dioxide dechlorination unit processes in series. The plant receives mostly domestic wastewater from the neighboring communities. The plant has an average flow of 3.8×10^4 m^3/day (10 mgd). The unchlorinated secondary effluent was pumped from the outlet of the secondary sedimentation system through a 15 cm (6 in) steel pipe to the holding tank at the research facility. The pumping rate was maintained at 35 l/sec (550 gpm). The secondary effluent was pumped from the holding tank to the chlorination pilot plant systems before being fed to the dechlorination pilot plants.

The sulfur dioxide and holding-tank impoundment dechlorination processes were investigated during this pilot plant study period, while the activated carbon adsorption dechlorination process was evaluated previously as a part of other research projects. The results of all three dechlorination pilot plant studies are presented together in this report.

DECHLORINATION WITH SULFUR DIOXIDE

Description of Pilot Plant

The pilot plant consisted of a chlorination and a dechlorination system in series. Two identical chlorine and sulfur dioxide contact tanks such as that shown in Figure 7 were used for this study. The contact tank had the flexibility of providing a two hour theoretical contact time (tank volume divided by flow rate) for either a 95 l/min (25 gpm) or a 190 l/min (50 gpm) flow. The tank had an adequate inlet flow distribution and a proper length


SULFUR DIOXIDE
ANALYZER
SULFONATOR
DRAIN
CHLORINATED EFFLUENT
CONTACT CHAMBER
DECHLORINATED EFFLUENT
MIXING CHAMBER
ACTIVATED CARBON
CHLORINATED EFFLUENT
CARBON FILTER
DECHLORINATED EFFLUENT
HOLDING TANK
CHLORINATED EFFLUENT
HOLDING TANK
DECHLORINATED EFFLUENT

NOTE:
---------- ELECTRICAL SIGNAL
———— LIQUID FLOW

Figure 6. Flow diagram of dechlorination pilot plant systems at Pomona, California.

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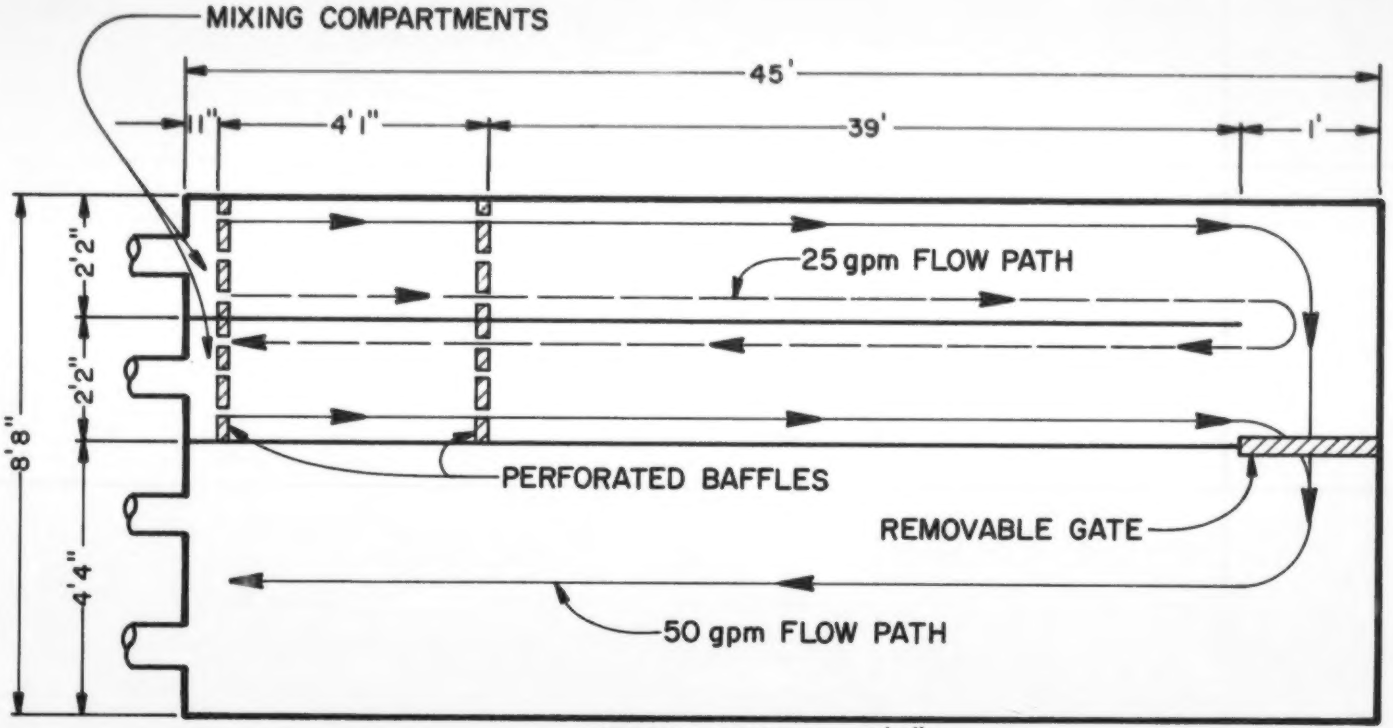
MIXING COMPARTMENTS
45'
11"
4'1"
39'
1'
25 gpm FLOW PATH
PERFORATED BAFFLES
REMOVABLE GATE
50 gpm FLOW PATH
8'8"
2'2"
2'2"
4'4"

(TANK DEPTH = 2'8")

1' = 12" = 30.48 cm
1gpm = 3.8 l/min.

Figure 7. Schematic diagram of chlorine contactor used in pilot studies.

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to width ratio (40:1) to approximate plug-flow. However, a tracer study conducted with ponticyl pink dye indicated the time for initial dye detection was approximately 52 minutes and the model time was 98 minutes.

As indicated in Figure 7, two perforated baffles were installed 28 cm (11 in) downstream from the inlet of the contact tank. These baffles were used to form 28 cm x 66 cm x 66 cm (11 in x 26 in x 26 in) compartments for chlorine or sulfur dioxide sparging and mixing. A 0.25 kW (0.33 hp) mixer equipped with a 1.6 cm (0.6 in) shaft and a 7.6 cm (3 in) diameter propeller was installed at an inclined angle in each of the compartments to provide an energy density of 2 kW per cubic meter (1 hp per 100 gallons) for chlorine or sulfur dioxide mixing. Both chlorine and sulfur dioxide solutions were made with tap water and were sparged through perforated PVC pipes at the bottom of each mixing compartment. Two additional perforated baffles were installed 1.5 m (5 ft) downstream from the inlets of the contact tank, as shown in Figure 7, to promote uniform flow in the tank.

A Fischer and Porter chlorine control system was used in the chlorination pilot plant, while a modified Wallace and Tiernan chlorinator was used as sulfonator for the dechlorination pilot plant. The chlorine controller was provided with a 3 to 500 percent proportional band adjustment mechanism and an automatic reset. A compound loop control was incorporated into the chlorine control system to compensate for flow variation.

Operation of Pilot Plant

Prior to the pilot plant operation, laboratory jar tests were first conducted with unchlorinated secondary effluent to determine the chlorine residual necessary to meet the 2.2 per 100 ml MPN total coliform standard of California for non-restricted recreational water reuse. The results are shown in Figure 8. As indicated in the figure, a chlorine residual of 6 mg/l seemed to be sufficient to meet the total coliform bacteria standard with a contact time of 120 minutes. However, the actual chlorine dosage was found to vary from approximately 8 mg/l to 14 mg/l in the daily pilot plant operations to meet the bacterial standard. The variations of chlorine dosage in response to the water quality changes had resulted in a wide range of chlorine residuals in the chlorinated effluent. The average residual chlorine in the chlorinated effluent was about 6 mg/l.

The sulfur dioxide feed control system employed only a feed forward chlorine residual signal to dechlorinate the chlorinated effluent. The sulfur dioxide was dosed in proportion to the chlorine measured in the chlorinated effluent, which fed into the dechlorination system. The residual chlorine was continuously monitored by a chlorine analyzer and a recorder. An electronic signal was sent from the analyzer to the sulfonator to control sulfur dioxide dosage based on chlorine residual. The sulfonator was readjusted to feed sulfur dioxide in direct proportion to the measured chlorine residual in the effluent feeding the dechlorination system.

The automatic mechanisms of the sulfonator system did not function successfully because of some malfunctions developed in the sulfur dioxide

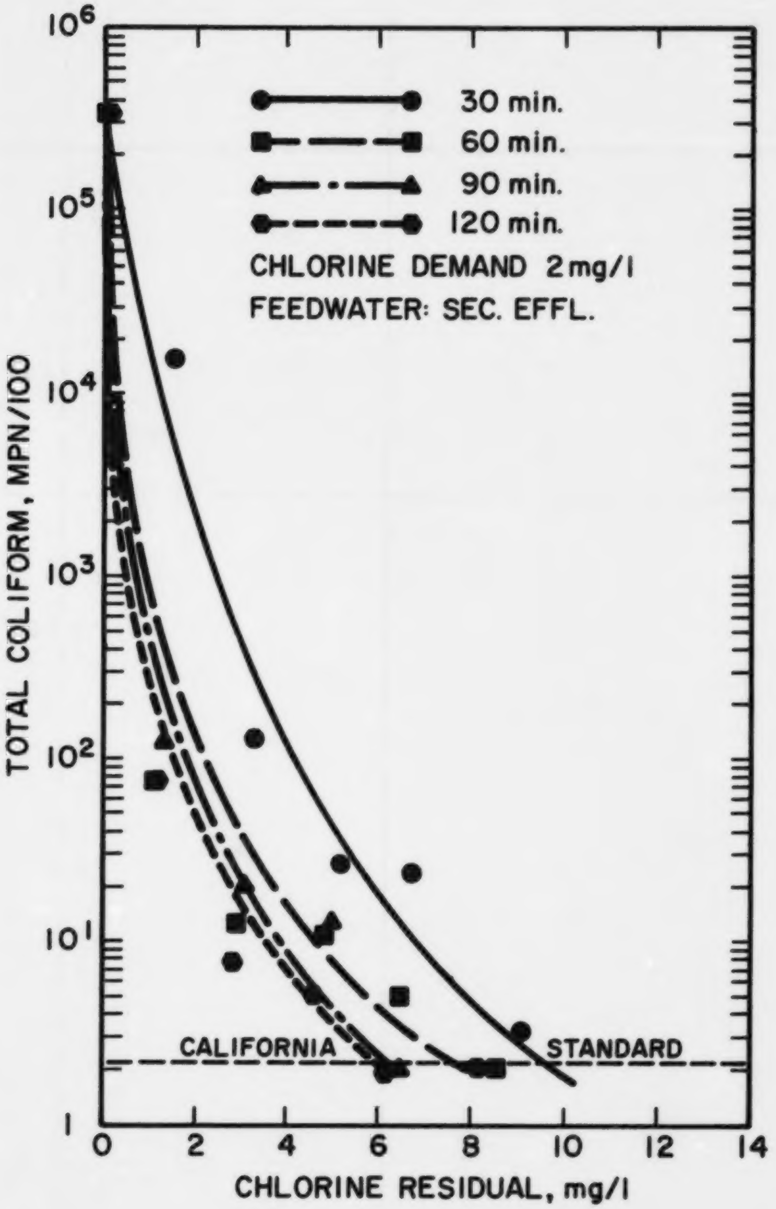

Figure 8. Chlorination of Pomona Water Reclamation Plant secondary effluent --laboratory jar tests.

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dispensing control. Therefore, the sulfonator was operated manually throughout most part of the dechlorination study. The sulfur dioxide dosage was manually preset to remove a specific chlorine residual in the chlorinated effluent, which was fed into the dechlorination system. Since the flow and residual chlorine were both very constant in the pilot plant testing, the removal of residual chlorine with a preset sulfur dioxide dosage could be reliably achieved. However, in a full scale plant operation where both flow and chlorine residual may vary substantially, a multiplier/ratio station for effectively monitoring the sulfonator may have to be employed.

A chlorine residual analyzer/recorder system was used in the pilot plant to monitor the residual chlorine in the dechlorinated effluent. However, the analyzer was found to be incapable of measuring chlorine residual after a brief period of non-chlorine detection in the dechlorinated effluent. Similar problems are expected in full-scale systems. Monitoring of the dechlorinated effluent to ensure the absence of residual chlorine, therefore, had to be done manually with grab samples collected several times a day. The residual chlorine was measured by the DPD ferrous ion titration method (31).

During the pilot plant study, the sulfur dioxide was added to the chlorinated effluent in the mixing chamber of the dechlorination system at ratios ranging from 1 to 2 mg/l of sulfur dioxide to 1 mg/l of residual chlorine. From the mixing chamber, the dechlorinated effluent was fed through the sulfur dioxide contact chamber to study bacterial aftergrowth and physical/chemical degradation of the dechlorinated effluent. The theoretical contact time in the contact chamber was about two hours.

Grab samples for bacteriological and water quality analyses before and after dechlorination were collected once to twice a day, while composite samples were also collected daily for total and dissolved chemical oxygen demand (TCOD and DCOD, respectively) and total dissolved solids (TDS) analyses. Both chlorination and dechlorination pilot plants were operated continuously from Monday to Friday every week.

Experimental Results and Discussion

Effects of Dechlorination on Effluent Quality Characteristics --

During the dechlorination study, a total of 177 sets of samples was collected under rather steady conditions during the period of October, 1977 through June, 1978. The average results of these analytical data are presented in Table 5.

As indicated in Table 5, effluent quality after dechlorination was generally improved. The total chlorine residual in the dechlorinated effluent was maintained consistently below detection limit. An average of 4 mg/l sulfite was detected in the dechlorinated effluent under the complete dechlorination conditions. Stoichiometrically, this excessive amount of sulfite may ultimately cause about one milligram of dissolved oxygen (DO) demand per liter of dechlorinated effluent discharged.

TABLE 5. AVERAGE WATER QUALITIES DURING PILOT SULFUR DIOXIDE DECHLORINATION STUDY

Water quality parameter	Secondary effluent	Chlorinated effluent (2 hr-contact)	Dechlorinated effluent (10 min-contact)	Dechlorinated effluent (2 hr-contact)
Total chlorine residual, mg/l	--	6.2	ND	ND
Dissolved oxygen, mg/l	1.7	4.1	6.0	6.1
Sulfite, mg/l $SO_3^=$	--	--	4.8	3.4
Median pH	7.3	7.2	7.1	7.1
Ammonia, mg/l N	12.3	11.7	9.7	9.9
TDS, mg/l	519	509	474	475
Sulfate, mg/l $SO_4^=$	108	106	100	100
Total COD, mg/l	37	35	30	30
Dissolved COD, mg/l	22	22	19	19
Turbidity, FTU	2.3	2.6	2.4	2.4
Suspended solids, mg/l	5	5	4	4
Temperature, ^oC	23.7	23.6	23.4	23.4
Alkalinity, mg/l $CaCO_3$	215	191	175	178

Notes: (1) The averages were based on 177 sets of samples.
(2) ND = not detectable (detection limit = 0.05 mg/l).

The dissolved oxygen was increased from a level of 4 mg/l in the chlorinated effluent to a level of 6 mg/l in the dechlorinated effluent through the sulfur dioxide dechlorination system. This improvement was attributed to the vigorous mixing provided in the sulfur dioxide mixing compartment of the dechlorination system. No further reaeration of the dechlorinated effluent was found necessary in the pilot plant study.

The hydrogen ions released during the sulfur dioxide dechlorination process caused a decrease of the alkalinity in the dechlorinated effluent. The limited amount of alkalinity reduction only slightly reduced the pH from 7.2 in the chlorinated effluent to 7.1 in the dechlorinated effluent. Therefore, it was not necessary to make any pH adjustment for the dechlorinated effluent during the pilot plant study . The average of the total dissolved solids was also slightly decreased from approximately 510 mg/l to 475 mg/l through the dechlorination process.

The other quality parameters, such as ammonia nitrogen, sulfate, total and dissolved COD, turbidity and suspended solids, were also reduced slightly through the dechlorination process. However, the reductions were not considered significant enough to warrant further explanation.

Effects of SO_2 Overdose on DO and pH --

Dissolved oxygen depletion and pH reduction after sulfur dioxide dechlorination were generally anticipated because of the reducing property of sulfur dioxide and the release of hydrogen ions in its reactions with water and residual chlorine. However, due to the moderate dosing of sulfur dioxide generally added in the dechlorination process, the effects of DO depletion and pH reduction were found insignificant in both full-scale plant survey and pilot plant study. These effects can be further minimized by the provision of a vigorous sulfur dioxide mixing and the availability of moderate level of alkalinity in the wastewater.

A brief study during the pilot plant operations showed an overdose of 50 mg/l of sulfur dioxide was necessary to produce any significant effects of DO depletion and pH reduction. Therefore, reaeration and pH adjustment may not be necessary for controlling DO depletion and pH reduction except when conditions such as high chlorine residual, low alkalinity, and poor sulfur dioxide control prevail in the operations.

Sulfur Dioxide/Chlorine Ratio --

According to the sulfur dioxide dechlorination reactions, a stoichiometric addition of 0.9 parts of sulfur dioxide per part of residual chlorine is adequate to achieve complete neutralization of residual chlorine. However, maintaining this ratio is often difficult because of equipment limitations. Moreover, the ratio does not assure complete removal of residual chlorine if other sulfur dioxide demand exists in the chlorinated effluent. Consequently, an overdosing of sulfur dioxide is generally practiced to comply consistently with the chlorine residual standard.

During the pilot plant study, the sulfur dioxide was manually adjusted to achieve complete dechlorination. It was found the SO_2/Cl_2 ratio varied from 1 to 2 in the pilot plant operations. The additional SO_2 demand of the chlorinated effluent was not easily identified. However, there was no difficulty in obtaining complete dechlorination as long as an excess of approximately 4 mg/l of sulfite was maintained in the dechlorinated effluent.

Bacteriological Aftergrowth --

Bacteria measured for this phase of work included total and fecal coliforms, total aerobic plate count at 35 ^{o}C, fecal streptococci, and Salmonella. All tests were performed in accordance with Standard Methods (31) except for the Salmonella spp. which were isolated using the methods of Kenner and Clark (32), as modified by Venosa et al (33), and recommended by Van Sluis and Yanko (34).

Figure 9 shows typical total coliform results for the chlorination and dechlorination pilot plant operations. An increase in total coliforms shortly after dechlorination was consistently observed in the dechlorinated effluent. It was presumed that the increase of total coliform bacteria after dechlorination might be due to either a recovery of the bacteria injured during chlorination or contamination during the detention period in the sulfur dioxide contact chamber. Contamination from the air was not considered likely since the sulfur dioxide contact chamber was covered with a plastic sheet throughout the pilot plant operations.

A special study conducted with filtered secondary effluent, instead of the unfiltered effluent employed during the routine pilot plant operations, was performed to determine if bacteriological aftergrowth would still occur after the removal of most suspended solids. These solids were suspected as a possible source of recontamination since they might shelter bacteria and thus prevent bacteria from being killed by chlorine. The filter employed in this study was a dual-media pressure filter, which reduced suspended solids from an average level of 5 mg/l in the secondary effluent to an average level of 2 mg/l in the filtered effluent. The results indicated that the same bacterial aftergrowth phenomenon was also observed in the filtered secondary effluent. Therefore, the limited amount of suspended solids in the pilot plant secondary effluent was disregarded as a significant contaminant responsible for the increased total coliform count after dechlorination.

Jar tests were performed in the laboratory to determine if the total coliform increase could be attributed to the recovery of the injured bacterial cells. A chlorinated secondary effluent sample from the chlorination pilot plant was collected in a sterilized bottle and then dechlorinated with sulfur dioxide solution (sulfurous acid). The results are summarized in Table 6. As indicated in the table, samples collected from the chlorination chamber in sterilized bottles containing a dechlorinating agent showed no increase in total coliform bacteria when held for the appropriate time. This indicated that the aftergrowth phenomenon was not due to revival of injured coliforms to any significant extent.

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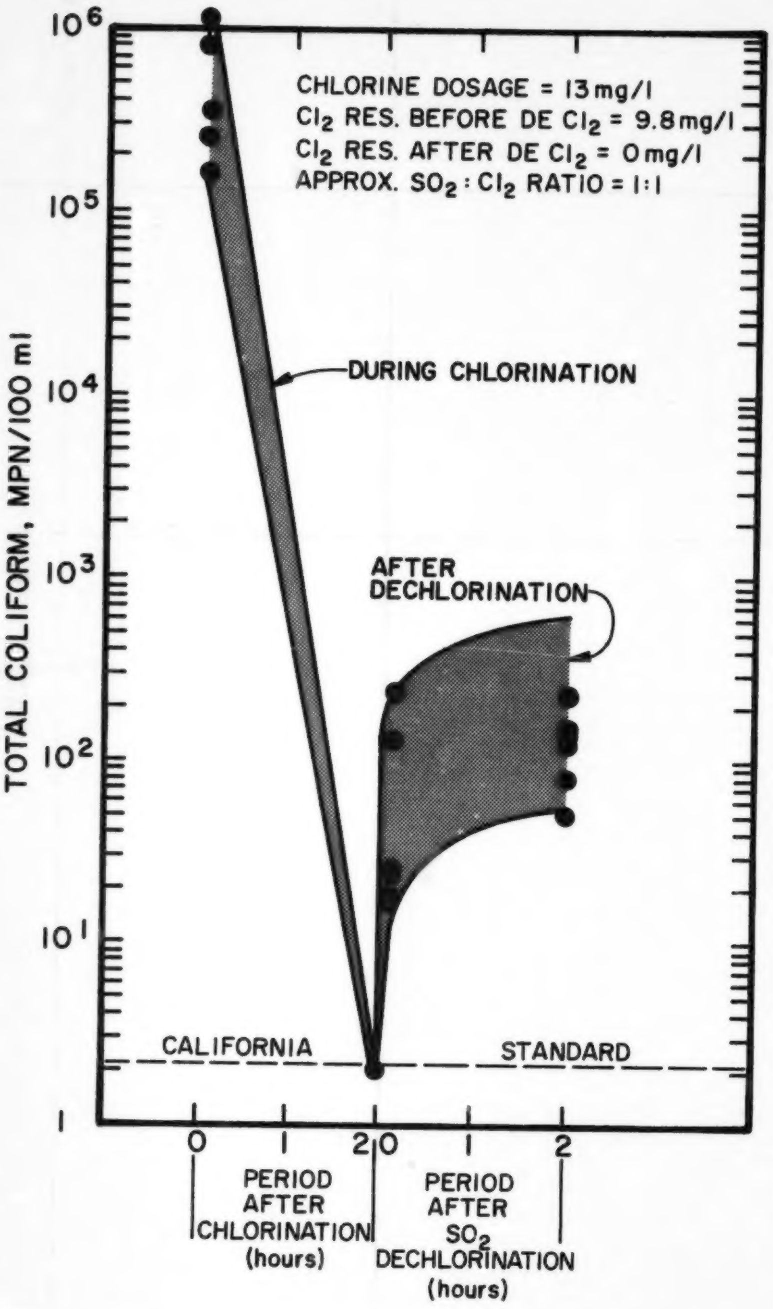

Figure 9. Pilot plant observation of total coliform before and after dechlorination with SO_2.

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TABLE 6. JAR TEST RESULTS OF BACTERIAL AFTERGROWTH AFTER DECHLORINATION

Experiment number	Chlorinated effluent (2 hrs)	Dechlorinated in sample bottle (10 min)	Dechlorinated in pilot plant tank (10 min)
1	2	2	49
2	<2	<2	79
3	5	2	33
4	2	2	49
5	2	2	33
6	2	<2	49
7	2	<2	490

Note: All results expressed as total coliform MPN per 100 ml.

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The sulfur dioxide dechlorination pilot system was subsequently used for further aftergrowth studies. The sulfur dioxide contact chamber and mixing compartment were thoroughly cleaned and disinfected. The disinfection was performed with an impoundment of chlorinated water (with chlorine residual of approximatley 10 mg/l) in the contact chamber for a period of about 64 hours. The system was then put in operation and the dechlorinated effluent samples were collected at 1, 2, 3, and 4 day intervals after startup. The typical results are presented in Figure 10. Total coliforms increased by about two orders of magnitude (100-fold) within the first three days. The increase seemed to level off after the initial three day period.

The gradual increase in total coliforms suggested that the source of contamination might be attributed to a buildup of bacterial growth in the sulfur dioxide contact chamber. Slime and scum buildup were consistently observed in the contact chamber a few days after startup.

Samples of slime and scum collected from the sulfur dioxide contact chamber contained very high concentrations of coliforms. The following samples were collected and tested on June 30, 1978:

1. Scum buildup on the side of the sulfur dioxide contact chamber at the water-air interface. Total and fecal coliforms, expressed as MPN per gram of dry scum material, were 1.9×10^8 and 2.8×10^6, respectively.

2. Dead insects and scum entrapped in foam floating on surface of contact chamber. Total and fecal coliforms were 6.0×10^6 and 6.0×10^5 MPN per gram of dry materials, respectively.

3. Final portion of the contact chamber before discharge point. Very light slime growth on all chamber surfaces. The slime could not be sampled directly, so the slime materials were stirred into the water and the mixed water from the chamber was sampled. Total and fecal coliforms were 39 and 23 MPN per 100 ml, respectively.

The above data seemed to indicate that the recontamination by the communities of microorganisms growing inside the sulfur dioxide contact chamber was primarily responsible for the bacterial aftergrowth in the dechlorinated effluent. In an experimental situation, like the pilot plant study, very strict control measures could control the growth of these communities of microorganisms and subsequent coliform contamination of the dechlorinated effluents. In actual practice, however, this type of control would not be possible.

Besides the total and fecal coliform analyses, other bacteriological analyses were performed. These results were presented graphically in Figure 11. Increases were found in the total plate count populations as well as the fecal coliforms. These increases (less than 0.5 log unit) were significantly lower than those found for the total coliforms. No significant change in the fecal streptococci counts was observed after dechlorination.

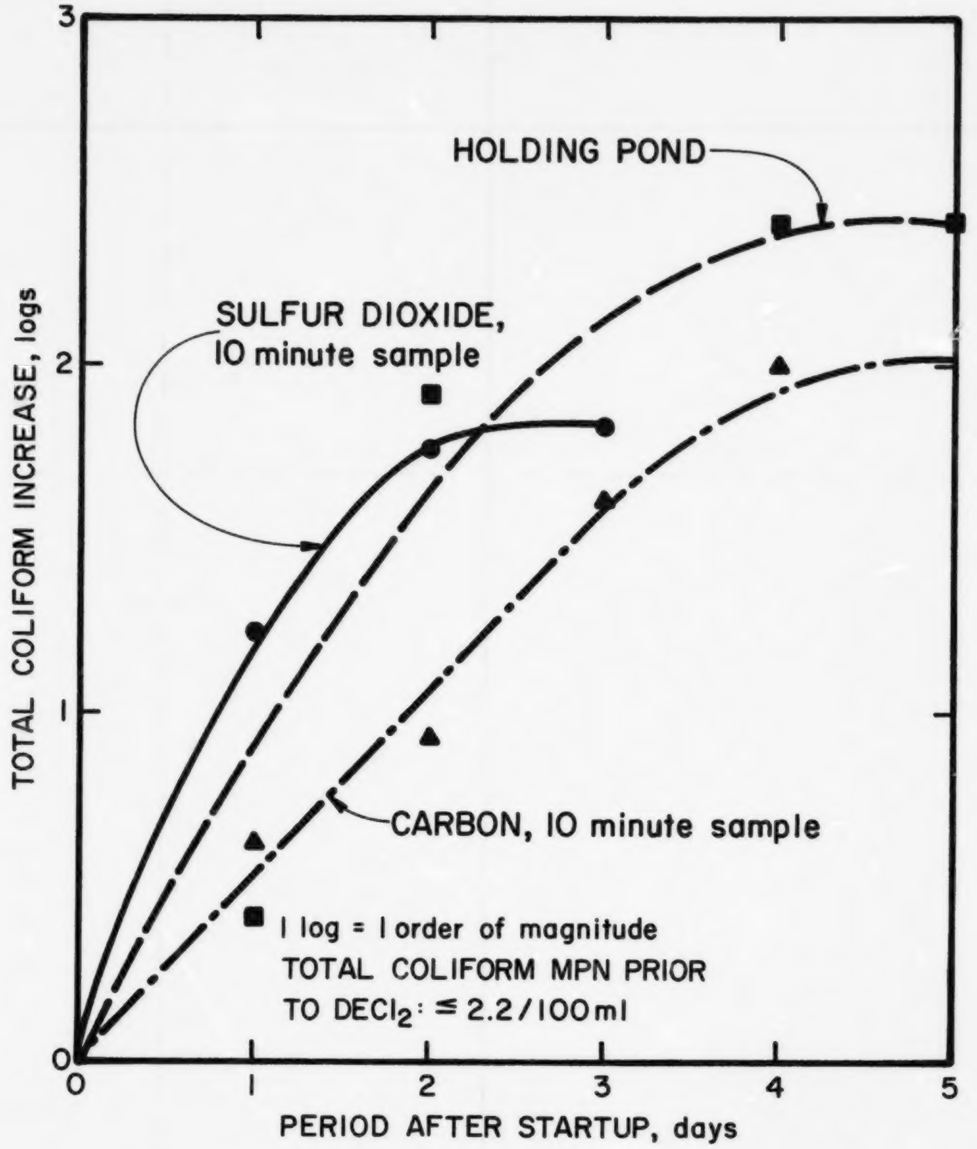

Figure 10. Rate of contamination after initial startup in clean dechlorination pilot plant systems.

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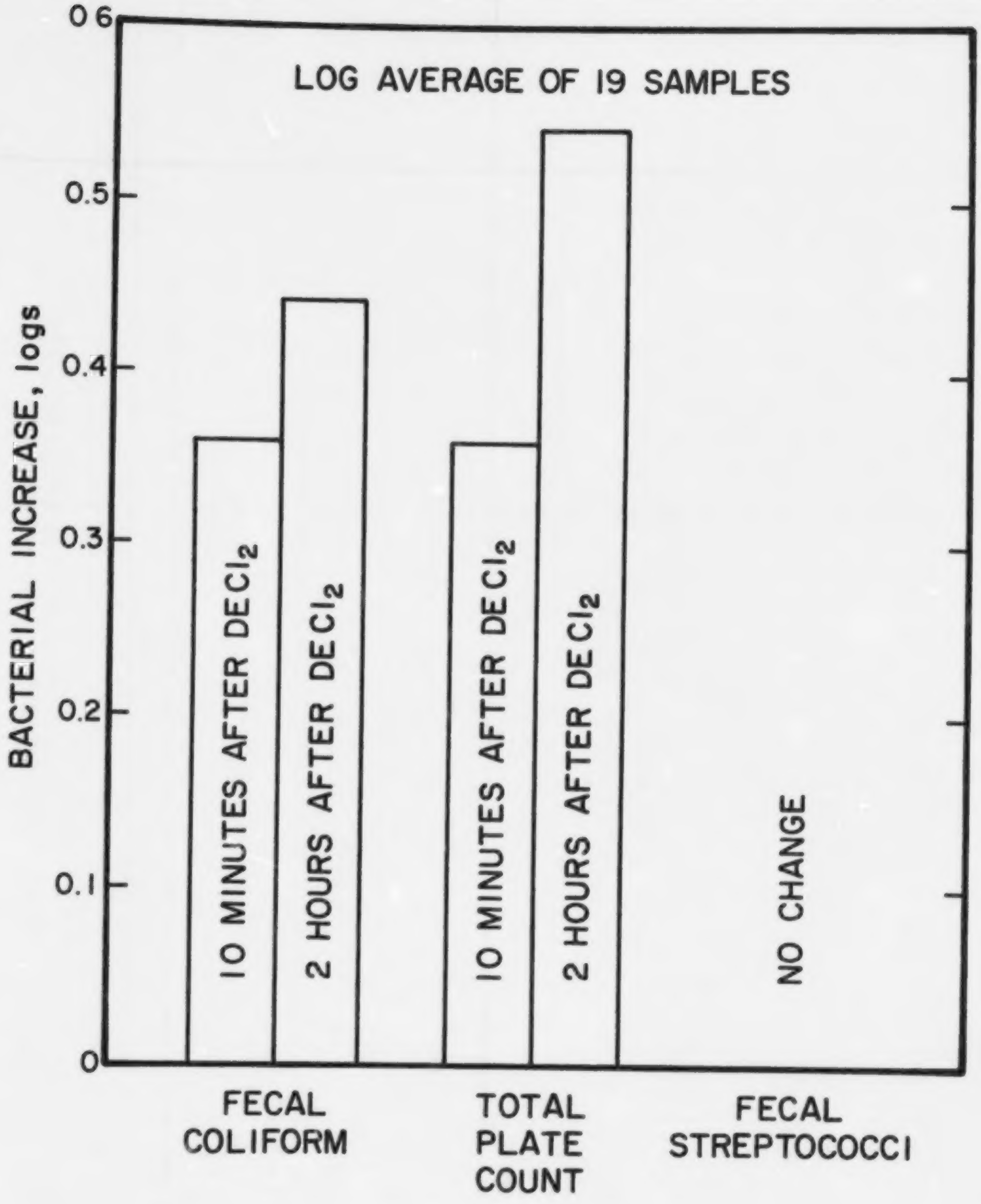

Figure 11. Bacterial responses in dechlorinated effluents of pilot plant studies.

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In addition to the above bacteriological tests, Salmonella analyses were also performed. Two enrichment media were employed to isolate the Salmonella: namely, dulcitol selenite broth (DSE) and tetrathionate broth (TB). Both have been shown to be effective for enriching Salmonella. Following enrichment, isolation and confirmation of Salmonella colonies were carried out. Isolation media used were Xylose Lysine Desoxycholate (XLD) and Bismuth Sulfite (BS). Confirmation of typical colonies was performed biochemically using Lysine Iron Agar, Triple Sugar Iron Agar, and Urea Broth, and serologically using Salmonella polyvalent-O antiserum. A total of 26 tests was conducted. All were qualitative tests since low numbers of Salmonella were anticipated due to chlorine disinfection of the water samples. The results provided an estimate of sampling volume size for the quantitative tests performed later.

Table 7 summarizes the qualitative results of the Salmonella tests. Only results where Salmonella were isolated in the unchlorinated secondary effluent are presented. Of the 26 unchlorinated secondary effluent samples, Salmonella were isolated in 15. Of these 15 samples, only three, or 20 percent of the 15 samples, showed the presence of Salmonella after dechlorination.

Table 8 shows the quantitative results for Salmonella tests. The procedure used was the same as the qualitative method except that 16 to 24 liter samples were filtered through a Whatman GF/F filter and diatomaceous earth under pressure; the filtrates were placed in 10 ml enrichment broth (both DSE and TB were used) and homogenized in a blender. The resulting homogenates were tested by the MPN Procedure, using tetrathionate broth at 37°C. No Salmonella were detected (detection limit = 0.05 Salmonella/l) in the dechlorinated effluent even though positives were found in the unchlorinated secondary effluent. The Salmonella counts for the unchlorinated secondary effluent ranged from 8 to 40 per liter of sample.

The results of the bacteriological aftergrowth study indicated that prevention of slime growth in the dechlorination system was not feasible. The growth appeared to be similar to that found in natural streams. The slime growth in dechlorinated effluent may be enhanced by the available nutrients in wastewater, the moderate ambient temperature, and the lack of toxic chlorine residuals. It is believed that the presence of chlorine residuals is an important factor in deterring the growth of microorganisms in the effluent and receiving waters.

Reliability of Process Instrumentation --

The chlorine residual was controlled automatically at an averaged level of 6 mg/l by a feedback sampling control system. The average chlorine dosage required to achieve this residual was about 10 mg/l. The chlorine analyzer was found to require a regular cleaning of the electrodes and weekly calibration. Periodic bleeding of the buffer solution lines was also necessary as part of the maintenance required of the analyzer. The buffer solution was added to maintain the pH of the sample within 4.0 to 4.5.

TABLE 7. SALMONELLA ISOLATIONS IN EFFLUENTS OF PILOT PLANT STUDIES WITH KNOWN SALMONELLA IN UNCHLORINATED SECONDARY EFFLUENT

Sampling date	Unchlorinated secondary effluent	Dechlorinated effluent
3/29/78	+	-
4/ 5/78	+	-
5/ 8/78	+	-
5/31/78	+	-
6/19/78	+	-
6/28/78	+	-
7/ 6/78	+	-
7/10/78	+	-
7/12/78	+	-
7/17/78	+	-
7/24/78	+	+
7/28/78	+	-
8/ 2/78	+	-
8/23/78	+	-
8/25/78	+	-

TABLE 8. QUANTITATIVE ANALYSES FOR *SALMONELLA* IN EFFLUENTS OF PILOT PLANT STUDIES

Sampling date	Unchlorinated secondary effluent (*Salmonella*/liter)	Dechlorinated effluent (*Salmonella*/liter)
8/15/78	10	<0.05
8/16/78	8	<0.05
8/17/78	40	<0.06

It was demonstrated in this pilot study that the dechlorination system would be best controlled by operating in manual mode. The sulfur dioxide dosage was manually preset to remove a specific chlorine residual in the chlorinated secondary effluent. This mode of operation was proved to be very successfull and reliable in the pilot plant study where both chlorine residual and flow were kept constant. Since the automatic sulfur dioxide feed control system did not function successfully, the system was bypassed in the early stage of the study and was never fully evaluated during this dechlorination pilot plant study.

As discussed previously, the chlorine analyzer was not functional for continuous monitoring of the trace amount of chlorine residual in the dechlorinated effluent. Laboratory titration methods are still believed to be the most reliable techniques for monitoring the efficiencies of dechlorination processes. However, it is very important to have a reliable on-stream chlorine monitoring system to constantly maintain the chlorine residuals below the allowable limits. Before such a system can be developed, an overdosing of sulfur dioxide to assure complete dechlorination seems to be an effective alternate solution.

DECHLORINATION WITH HOLDING-TANK IMPOUNDMENT

Description of Pilot Plant

As shown in Figure 7, the 95 l/min (25 gpm) pilot plant flow would only occupy one-half of the chlorine contactor for a two hour theoretical contact time. Therefore, the other half of the chlorine contactor was used as a holding tank for this phase of the dechlorination study. The holding tank was open to the air without any cover to simulate the natural pond situation. The same chlorination pilot plant system used in the sulfur dioxide dechlorination pilot plant study was employed to provide chlorinated secondary effluent for this study.

Operation of Pilot Plant

Chlorinated secondary effluent from the pilot plant was diverted into the holding tank for dechlorination by impoundment (i.e., dissipation of residual chlorine by volatilization, sunlight destruction, etc.). Samples were collected from the holding tank periodically and tested for residual chlorine and coliforms. The batch experiment was repeated to see if the results could be reproduced under similar operating conditions.

Experimental Results and Discussion

The dissipation of free chlorine in the absence of sulfur dioxide addition was briefly investigated in the laboratory. Jars containing chlorinated nitrified-secondary effluent and chlorinated distilled water were allowed to stand for 72 hours. The initial chlorine residuals for both types of waters were about 1.5 mg/l as free chlorine. Figure 12 shows the dissipation of chlorine in both types of waters. As shown, no chlorine residual was detected in the chlorinated nitrified-secondary effluent after two hours of standing. By comparison, it took about 72 hours for the residual chlorine to

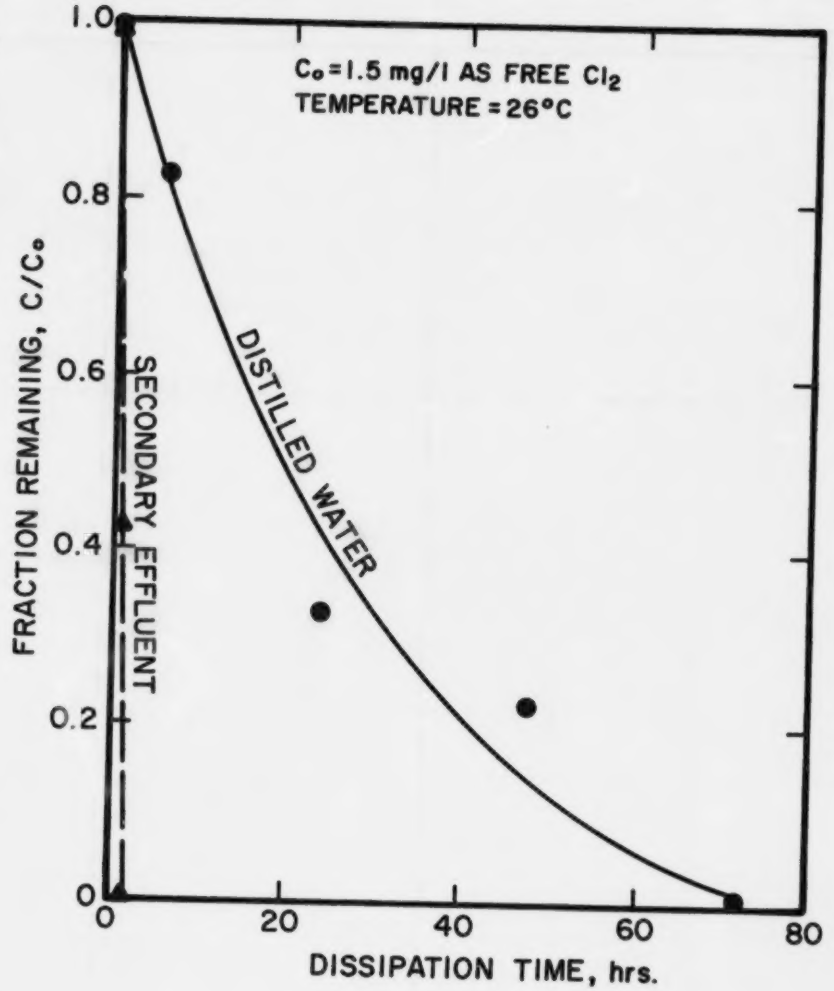

Figure 12. Dissipation of free chlorine in distilled water and secondary effluent.

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dissipate in distilled water. The more rapid dissipation rate of chlorine in the nitrified-secondary effluent was attributed to the presence of more chlorine demand substances.

The dissipation of chlorine residual in its various forms was also investigated in the laboratory. Jars of chlorinated nitrified-secondary effluent containing approximately 1.4 mg/l of free chlorine, 0.6 mg/l of monochloramine, 1.4 mg/l of dichloramine, and 0.8 mg/l of nitrogen trichloride were allowed to stand for 72 hours. All forms of chlorine residuals were determined by DPD titration method (31). Figure 13 shows the dissipation results for free chlorine, monochloramine, dichloramine, and nitrogen trichloride. As shown in the figure, the free chlorine and nitrogen trichloride exhibited almost similar dissipation rate with virtually no detectable concentration after two hours of standing. The dissipation rates of these two forms were much faster than those of monochloramine and dichloramine. The monochloramine and dichloramine were still measured in the secondary effluent after 72 hours of standing under laboratory conditions. The relative rates shown in Figure 13 may be influenced by differences in initial concentrations of various chlorine forms, but the trend seems to be clear that both monochloramine and dichloramine forms are dissipated slowly.

The pilot plant holding-tank dechlorination results are summarized in Table 9. By extrapolating the data, the holding times required for complete dechlorination by natural dissipation were estimated to be about 68 and 56 hours, respectively, for initial total chlorine residuals of 3.7 mg/l and 2.7 mg/l. Using data from Figure 13 as well as Table 9, a relationship between period of impoundment and initial total chlorine residual for complete dechlorination in a holding tank can be derived as shown in Figure 14. Based on Figure 14, the total impoundment time for dechlorinating a chlorinated effluent with 5 mg/l of total chlorine residual is approximately 96 hours.

As indicated in Table 9, the initial total coliform density was slightly increased during the initial 43 hour period but the fecal coliforms remained relatively unchanged. As soon as the total chlorine residual had completely dissipated, a significant increase in the total and fecal coliforms was found. The degree of increase in total coliforms was quite similar to that found with sulfur dioxide dechlorination. Approximately two orders of magnitude of total coliform increase were observed in the dechlorinated effluent. The fecal coliform increase was about 1 log unit. No other water quality data are presented for these holding tank pilot plant studies since no significant changes other than chlorine residual and coliforms were observed during the study.

DECHLORINATION WITH ACTIVATED CARBON ADSORPTION

Description of Pilot Plant

In early 1972, the Sanitation Districts of Los Angeles County initiated a pilot plant study at their Pomona Research Facility to evaluate the flow scheme, shown in Figure 15, for their proposed Malibu Water Reclamation Plant. The objectives of the treatment were to produce a treated effluent

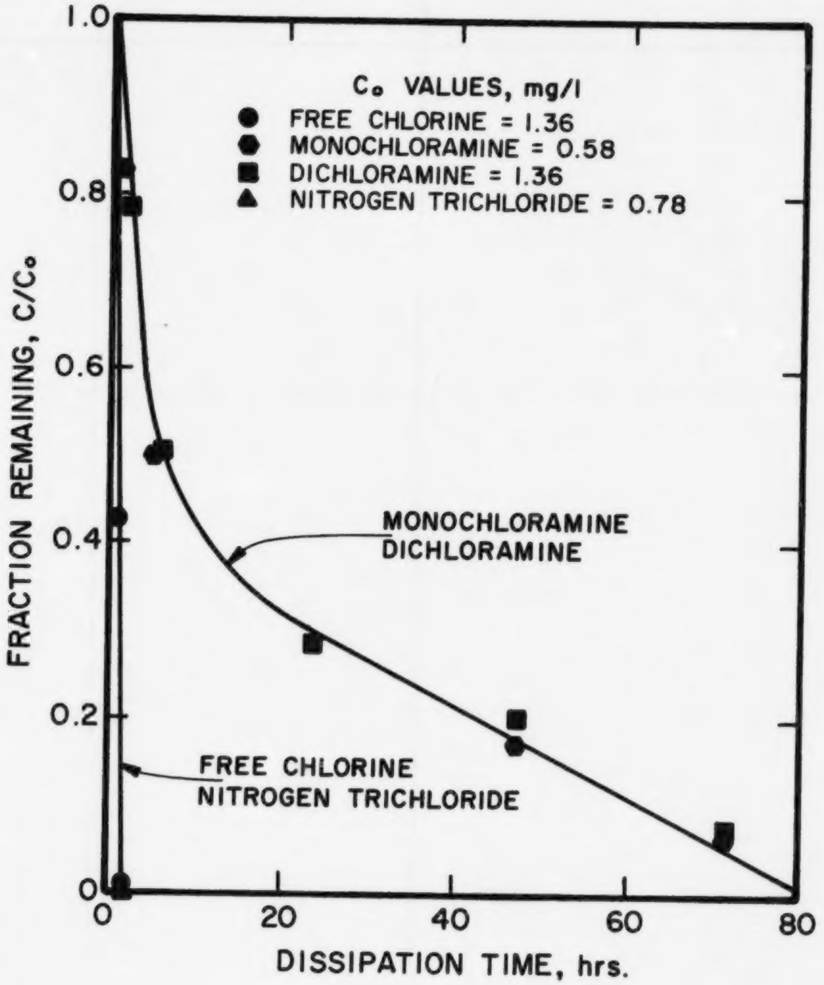

Figure 13. Dissipation of chlorine residual in secondary effluent.

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TABLE 9. EFFECTS OF HOLDING TIME ON RESIDUAL CHLORINE AND REMAINING ORGANISMS

Sampling date	Accumulated holding time (hrs)	Residual chlorine (mg/l)					Remaining organisms (MPN/100ml)	
		Free	Mono	Di	Tri	Total	Total coliforms	Fecal coliforms
6/27/78	0	0	3.5	0.2	0	3.7	5	<2
6/28/78	19	0	2.4	2.2	0	2.6	2	<2
6/28/78	24	0	1.1	0.1	0	1.2	2	<2
6/29/78	43	0	0.5	0	0	0.5	23	2
6/30/78	67	0	0	0.1	0	0.1	7.9x10²	33
7/ 3/78	0	0	2.6	0.1	0	2.7	<2	<2
7/ 5/78	42	0	0.2	0	0	0.2	17	2
7/ 5/78	48	0	0.1	0.1	0	0.2	49	13
7/ 6/78	66	0	0	0	0	0	3.3x10²	49

Notes:
1. Temperature-30°C.
2. Underlined numbers show coliform count is still within the 95 percent confidence limit of the coliform count at zero holding time.
3. Weather condition - sunny.

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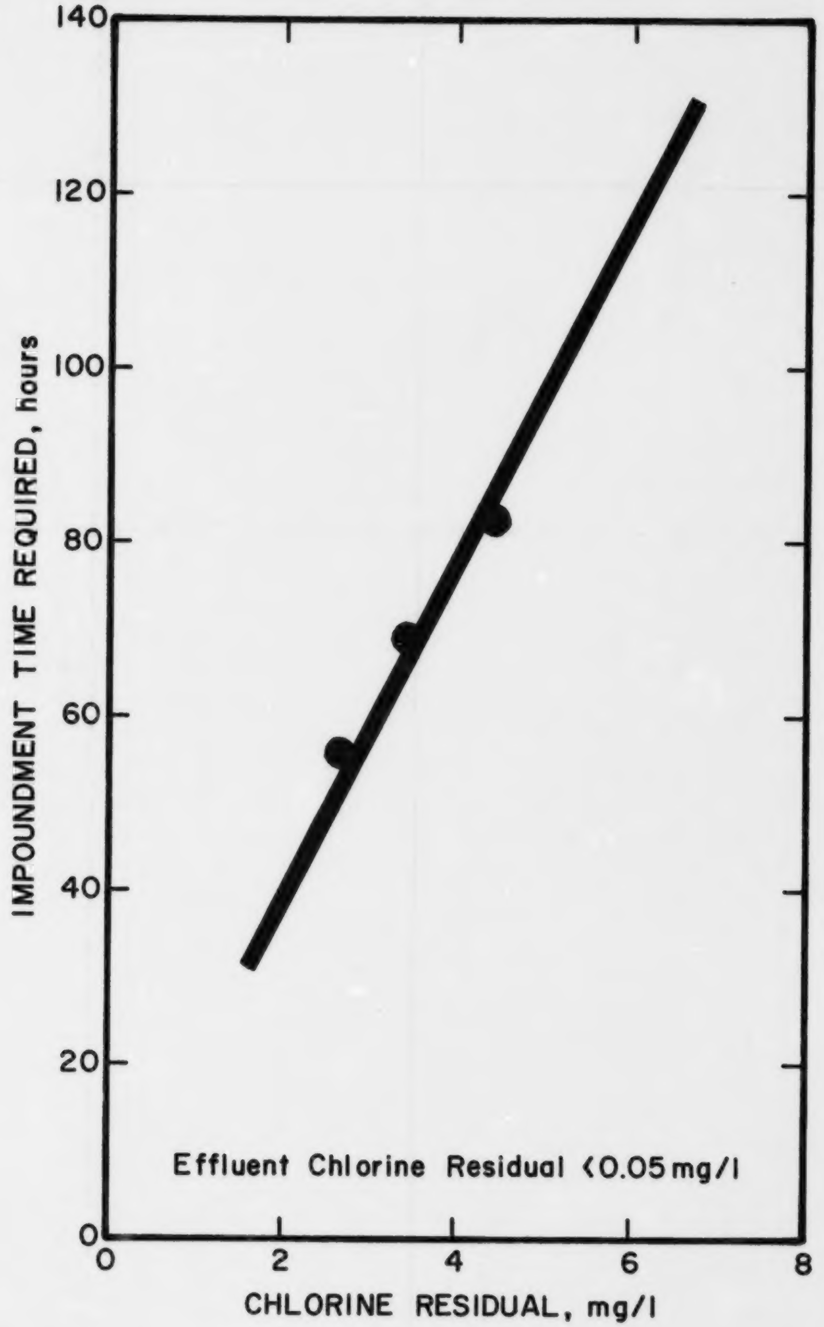

Figure 14. Impoundment time required for dissipation of chlorine residual.

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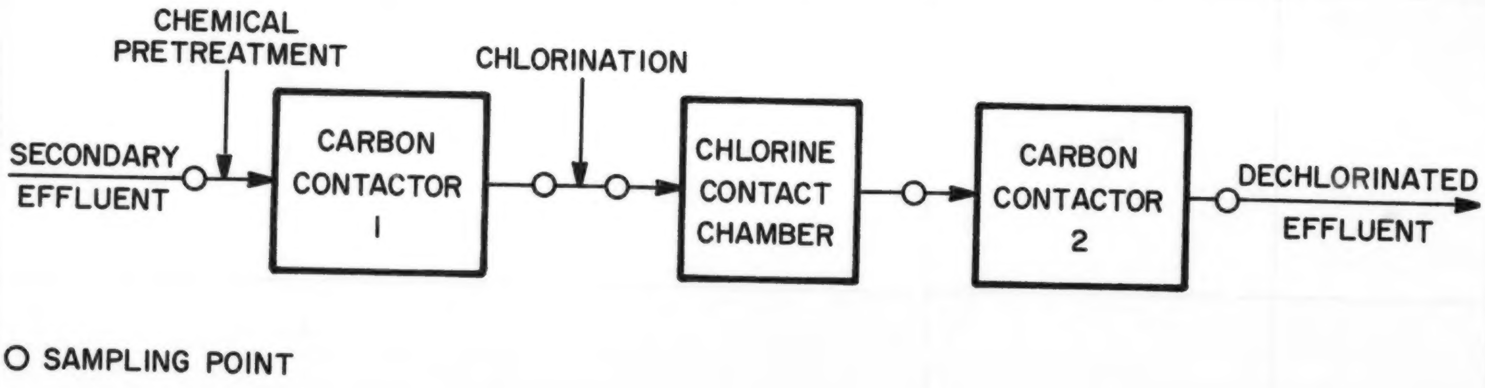
CHEMICAL PRETREATMENT
CHLORINATION
SECONDARY EFFLUENT
CARBON CONTACTOR 1
CHLORINE CONTACT CHAMBER
CARBON CONTACTOR 2
DECHLORINATED EFFLUENT
○ SAMPLING POINT

Figure 15. Carbon dechlorination flow scheme.

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free of viruses and chlorine residual and to meet the water quality standards for non-restricted recreational water reuse. The pilot plant study was completed in December, 1974.

The pilot plant consisted of first-stage carbon contactor, chlorine contact tank, and second-stage carbon contactor in series. The first-stage carbon contactor was to remove most of the suspended solids, organic constituents and possibly viruses to enhance the efficiency of the disinfection process. Chlorine was used as the disinfectant for the kill of viruses and bacteria to meet the disinfection standards. Finally, the chlorinated effluent was dechlorinated by the second-stage carbon contactor. The second-stage carbon contactor was also designed to provide additional removal of organics and viruses to assure the effluent free of viruses.

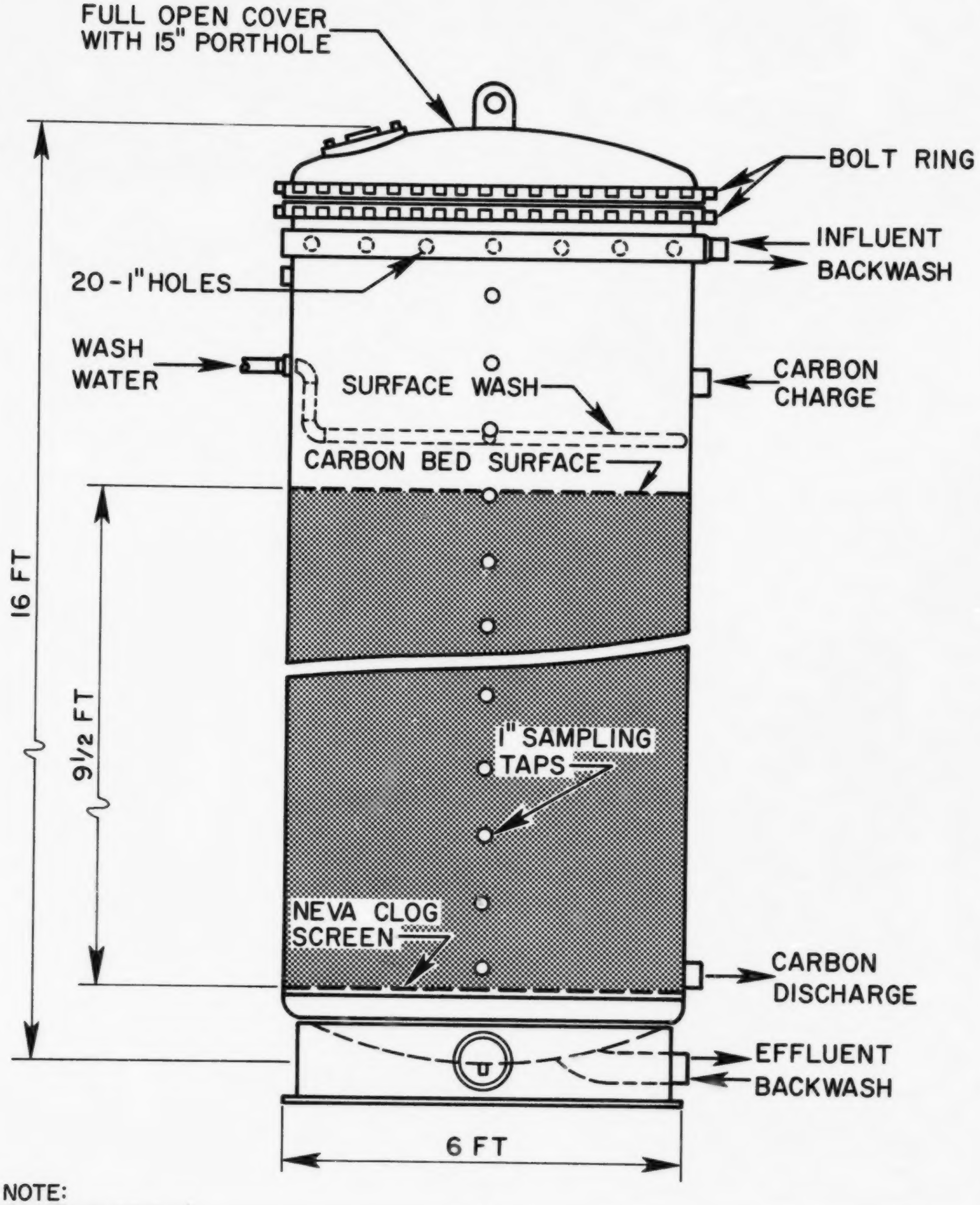
An identical design was used for both first-stage and second-stage carbon contactors. As shown in Figure 16, the carbon contactor was a steel tank measuring 1.8 m (6 ft) in diameter and 4.9 m (16 ft) in height. Carbon depth in the contactor was about 2.9 m (9.5 ft). Sampling taps were provided at various depths of the contactor. Both contactors were coated with corrosion-inhibiting bitumastic coal-tar epoxy coating. The Calgon Filtrasorb 300, with 8 x 30 mesh size, granular activated carbon was used in the first-stage carbon contactor, while the finer Calgon Filtrasorb 400, with 12 x 40 mesh size, granular activated carbon was used in the second-stage carbon contactor. Table 10 shows the average characteristics of the virgin Filtrasorb 300 and Filtrasorb 400 granular activated carbons.

A Wallace and Tiernan chlorinator was used to control the chlorine dosage. The chlorine was carried by tap water and the solution was mixed with the first-stage carbon effluent through a Venturi device. The chlorinated water was then directed into a 45 m^3 (12,000 gallons) steel chlorine contact tank. The tank was well baffled to provide an actual detention time as close to the theoretical detention time as possible. The tank was covered during the pilot plant study.

Pilot Plant Operation

The pilot plant was operated continuously at an average flow of 12.6 l/sec (200 gpm). At this flow rate, the empty-bed detention time for both first-stage and second-stage carbon contactors was approximately 10 minutes each. The modal detention time in the chlorine contact tank was determined to be about 45 minutes in a special dye tracer study.

The secondary effluent from the Pomona Water Reclamation Plant was first pretreated with alum in the dosage range of 5 to 10 mg/l and 0.1 mg/l of Calgon WT-3000 anionic polymer before being fed into the first-stage carbon contactor. The carbon contactors were operated in a down-flow and pressurized mode. The chlorine dosage was maintained within the range of 10 to 20 mg/l to provide an average total chlorine residual of 10 mg/l to meet the disinfection standards. The effluent of the second-stage carbon contactor was monitored for the breakthrough of chlorine residual. At such time when the chlorine breakthrough was detected, both contactor carbon media were


FULL OPEN COVER
WITH 15" PORTHOLE
BOLT RING
INFLUENT
BACKWASH
20 - 1" HOLES
WASH
WATER
SURFACE WASH
CARBON
CHARGE
CARBON BED SURFACE
16 FT
9½ FT
1" SAMPLING
TAPS
NEVA CLOG
SCREEN
CARBON
DISCHARGE
EFFLUENT
BACKWASH
6 FT

NOTE:
1' = 12" = 30.48 cm

Figure 16. Schematic diagram of carbon contactor used in pilot study.

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TABLE 10. VIRGIN CARBON CHARACTERISTICS OF ACTIVATED CARBON USED IN PILOT STUDY

Carbon characteristics		Calgon Filtrasorb 300 (8 x 30 mesh)	Calgon Filtrasorb 400 (12 x 40 mesh)
Iodine number, mg/g		984	1062
Molasses number		222	237
Methylene blue no., mg/g		271	275
Apparent density, g/cm^3		0.484	0.463
Ash, %		5.5	5.8
Mean particle dia., mm		1.6	1.0
Sieve analysis: % retained on no.	8	4.2	
	10	16.3	
	12	25.7	1.8
	14	18.7	10.3
	16	16.8	24.9
	18	10.2	20.8
	20	4.9	14.8
	30	2.6	20.6
	40		6.0
	Pan	0.6	0.8

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thermally regenerated with a multiple hearth carbon regeneration system at the Pomona Research Facility. The description and operation of the carbon regeneration system were presented elsewhere (34).

The first-stage carbon contactor was equipped with an automatic flow and backwash control. The interval of backwashing was controlled by a preset total headloss of 138 kN/m^2 (20 psi) in the contactor, and it was found to vary between 10 and 18 hours, depending on the quality of secondary effluent. The second-stage carbon contactor was backwashed manually once every two weeks of operation.

Composite samples were collected daily at various process monitoring points, as indicated in Figure 15, for general water quality analyses. Special grab samples were also taken as often as necessary for the analyses of chlorine residuals, total and fecal coliforms. All analyses were performed according to the Standard Methods procedures. In addition, some virus samples were also collected for monitoring the efficiency of virus removal under this mode of treatment operation. The virus results are presented elsewhere (35).

Results and Discussion

Water Quality Effects --

The average water qualities of the samples collected at various sampling points during the study are presented in Table 11. The averages of the total chlorine residuals and total coliforms were calculated with data obtained from those sampling days when the total coliforms in the chlorinated effluent were equal to or less than 2.2 MPN per 100 ml. Since the carbon regeneration was conducted whenever the chlorine residual was detected in the dechlorinated effluent, no chlorine residual was detected during normal operations of the carbon dechlorination pilot plant. The other water quality averages in Table 11 were based on data collected during the entire dechlorination study.

As indicated in Table 11, the chemical and physical properties of the dechlorinated effluent were substantially improved after the carbon adsorption process. The chlorine residuals were also effectively removed by the activated carbon. The pH values of the dechlorinated effluent were only slightly lower than those of pre-chlorination samples, and thus no pH adjustment was found necessary to correct any unfavorable pH conditions.

Bacteriological Aftergrowth --

As shown in Table 11 and Figure 10, total coliforms increased by about two orders of magnitude in the carbon dechlorinated effluent. The pattern of the gradual increase of total coliforms in the dechlorinated effluent with respect to the carbon operation time seemed to be responsive to the buildup of microorganisms in the carbon bed. Therefore, the bacteriological aftergrowth observed in the carbon dechlorinated effluent was believed to be the result of contamination by the growth of microorganisms in the carbon bed.

TABLE 11. AVERAGE WATER QUALITIES DURING CARBON DECHLORINATION STUDY

Water quality parameter	Secondary effluent	First-stage carbon effluent	Chlorinated effluent	Second-stage carbon effluent
Median pH	7.6	7.4	--	7.3
Total COD, mg/l	39	20	--	13
Dissolved COD, mg/l	25	16	--	10
Color, units	33	15	--	4
Turbidity, FTU	8.1	2.3	--	2.1
Suspended solids, mg/l	13	3	--	2
Total chlorine residual, mg/l	--	--	10.7	ND
Total coliforms, MPN/100 ml	--	3.04×10^5	< 2.2	310

Notes: (1) ND = not detected (detection limit = 0.05 mg/l).
(2) Based on 54 sets of data.

Based on some limited amount of data on the fate of fecal coliforms through the carbon dechlorination contactor, similar aftergrowth of fecal coliforms was observed in the dechlorinated effluent. The extent of aftergrowth was about one order of magnitude increase, which was about one-tenth of the increase of total coliforms.

Carbon Capacity for Dechlorination --

Dechlorination by granular activated carbon was found to be very effective with respect to either free chlorine or chloramine residuals. The removal seemed to be controlled primarily by the accumulated dosage of total chlorine residual, instead of the instant loading level of total chlorine residual. This would simplify the monitoring of residual chlorine in the dechlorinated effluent. The detection of chlorine breakthrough seems to be adequate for process monitoring.

The carbon capacity for dechlorination with 0.1 mg/l residual chlorine as control limit was found to vary between 0.19 kg and 0.22 kg of total chlorine residual applied per kg of activated carbon in the dechlorination contactor. The capacity was increased to approximately 0.27 kg of total chlorine residual per kg of carbon when 0.5 mg/l of chlorine residual was used as a control limit for dechlorination. The regeneration of carbon did not seem to create any significant effects on the carbon capacity for dechlorination. The dechlorination function of the carbon was not shown to interfere with the functions of chemical oxygen demand and color removals by the carbon.

With very limited data obtained with a small scale carbon dechlorination system prior to this 12.6 l/sec (200 gpm) large scale study, the carbon capacity was found to be slightly increased from an average of 0.17 kg to 0.21 kg of total chlorine residual applied per kg of activated carbon, if carbon particle size was decreased from 8 x 30 mesh (Calgon Filtrasorb 300) to 12 x 40 mesh (Calgon Filtrasorb 400). This finding was the reason for selection of Filtrasorb 400 for this large scale carbon dechlorination pilot plant study.

Chlorine Profile in Carbon Bed --

Figure 17 shows some typical chlorine residual profiles for the dechlorination carbon contactor on a semi-log plot. To a first approximation each 30 cm (1 ft) of carbon bed near the upstream end removed about 20 percent of the total chlorine residuals from the water entering it. The removal rate was increased to approximately 30 percent every 30 cm (1 ft) of carbon bed near the downstream end of the contactor.

Table 12 compares chlorine residual profiles taken when free chlorine was detected in the influent to the chlorine contactor with similar profiles taken on two days (9/24/74 and 10/1/74) when the influent showed only a combined chlorine residual. As indicated in Table 12, the "monochloramine residual" was removed more rapidly than the "dichloramine residual" on those "free chlorine day" profiles. The "dichloramine residual" was found to decline slowly with no sharp drop to zero. This seems to support the theory

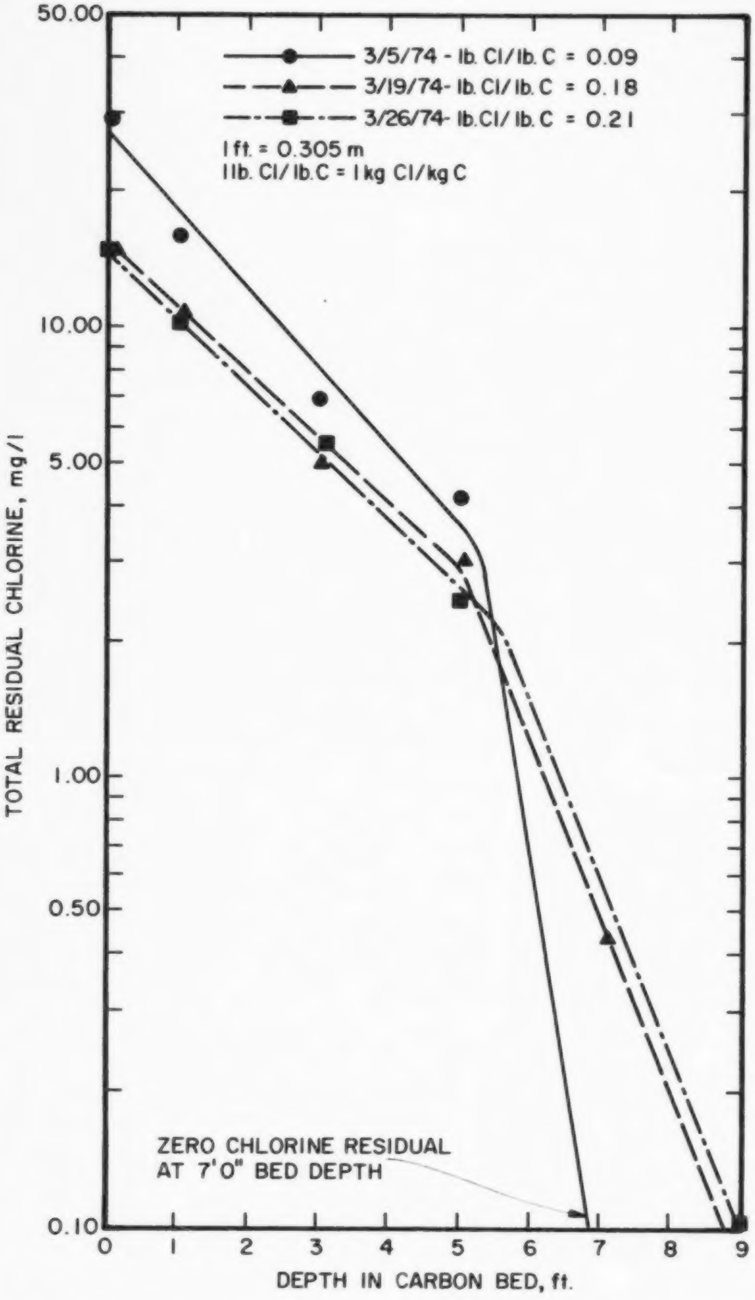

Figure 17. Chlorine profile in dechlorination carbon contactor

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TABLE 12. CHLORINE PROFILES IN CARBON BED FOR DECHLORINATION

Sampling date	Type of residual chlorine (mg/l)	Chlorine contactor		Depth below top of carbon (ft)						Second stage carbon effluent
		Inf.	Eff.	0	1	3	5	7	9	
8/27	Free	9.2	1.4	0	0	0	0	0	0	0
	Monochloramine	0	0	5.3	0.4	0	0	0	0	0
	Dichloramine	2.4	1.4	1.8	0.6	0.1	0.1	0.1	0.1	0.1
	Trichloramine	0	0	0	0	0	0	0	0	0
9/ 3	Free	5.2	4.0	0	0	0	0	0	0	0
	Monochloramine	0	0	3.6	0	0	0	0	0	0
	Dichloramine	2.0	1.5	1.4	0.5	0.4	0.3	0.2	0.1	0.3
	Trichloramine	4.6	0.6	0	0	0	0	0	0	0

TABLE 12. CHLORINE PROFILES IN CARBON BED FOR DECHLORINATION (Cont)

Sampling date	Type of residual chlorine (mg/l)	Chlorine contactor Inf.	Chlorine contactor Eff.	Depth below top of carbon (ft) 0	1	3	5	7	9	Second stage carbon effluent
10/ 8	Free	8.0	0	0	0	0	0	0	0	0
	Monochloramine	-	7.2	7.2	1.1	0.3	0	0	0	0
	Dichloramine	1.9	1.8	0.3	0.6	0	0.2	0.2	0	0
	Trichloramine	1.4	0	0.7	0	0	0	0	0	0
10/29	Free	10.5	0	3.9	0	0	0	0	0	0
	Monochloramine	1.1	1.2	0	0.2	0.1	0	0	0	0
	Dichloramine	1.2	1.2	1.6	0.8	0.5	0.3	0.1	0.1	0.1
	Trichloramine	0	0	0	0	0	0	0	0	0

TABLE 12. CHLORINE PROFILES IN CARBON BED FOR DECHLORINATION (Cont.)

Sampling date	Type of residual chlorine (mg/l)	Chlorine contactor Inf.	Chlorine contactor Eff.	Depth below top of carbon (ft) 0	1	3	5	7	9	Second stage carbon effluent
11/ 6	Free	7.3	8.2	3.3	0	0	0	0	0	0
	Monochloramine	0.5	0.4	0.5	0.5	0.1	0.1	0	0	0
	Dichloramine	1.9	1.9	1.6	1.0	0.7	0.4	0.4	0.3	0.3
	Trichloramine	2.1	0	0	0	0	0	0	0	0
11/12	Free	6.4	5.4	9.1	0.7	0	0	0	0	0
	Monochloramine	0.4	0.3	0.4	0.1	0.1	0	0	0	0
	Dichloramine	2.4	2.2	2.5	1.5	1.3	0.9	0.1	0.5	0.5
	Trichloramine	0	1.8	0.6	0	0	0	0	0	0

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TABLE 12. CHLORINE PROFILES IN CARBON BED FOR DECHLORINATION (Cont)

Sampling date	Type of residual chlorine (mg/l)	Chlorine contactor Inf.	Chlorine contactor Eff.	Depth below top of carbon (ft) 0	1	3	5	7	9	Second stage carbon effluent
11/20	Free	10.4	8.9	8.9	0	0	0	0	0	0
	Monochloramine	0.6	0.6	0.4	0.8	0.2	0.8	0	0	0
	Dichloramine	2.2	2.0	1.7	1.1	0.8	0.6	0.1	0.4	0.2
	Trichloramine	1.5	1.8	1.2	0	0	0	0	0	0
9/24	Free	0	0	0	0	0	0	0	0	0
	Monochloramine	13.6	12.8	12.4	5.1	0	0	0	0	0
	Dichloramine	0.5	0.4	0.4	0	0	0.1	0	0	0
	Trichloramine	0	0	0	0	0	0	0	0	0

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TABLE 12. CHLORINE PROFILES IN CARBON BED FOR DECHLORINATION (Cont)

Sampling date	Type of residual chlorine (mg/l)	Chlorine contactor		Depth below top of carbon (ft)						Second stage carbon effluent
		Inf.	Eff.	0	1	3	5	7	9	
10/ 1	Free	0	0	0	0	0	0	0	0	0
	Monochloramine	10.8	11.3	11.3	4.4	0	0	0	0	0
	Dichloramine	0.5	0.5	0.6	0	0	0	0	0	0
	Trichloramine	0	0	0	0	0	0	0	0	0

Notes: (1) 1 ft = 0.305m
(2) Sampling dates of 9/25 and 10/1 were for normal operating conditions without free chlorine residual in the chlorine contactor influent sample.

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of the formation of the persistent N-chlororganic nuisance residuals by the free chlorine and the organic nitrogen compounds in the water. According to White (13), the free chlorine could react with the organic nitrogen compounds such as creatinine, and the product of such reaction would cause a false "dichloramine" reading by the standard analytical procedure. Therefore, premature chlorine breakthrough may occur in the presence of free chlorine residual and organic nitrogen compounds. The bactericidal and toxic effects of such nuisance residuals are still unknown.

Process Reliability --

The variation of the total chlorine residuals for chlorinated and dechlorinated effluents during the first sequence of this pilot plant study are illustrated in Figure 18. As indicated in the figure, the total chlorine residuals of the chlorinated effluent fluctuated within a rather wide range of 2.6 mg/l to 15.1 mg/l. However, the chlorine residuals in the dechlorinated effluent appeared to remain consistently under the detection limit of 0.05 mg/l throughout the entire sequence of operation. The sequence was terminated after two consecutive samples showing detectable chlorine residuals. Similar reliability was repeatedly demonstrated in other sequences of pilot plant operations. Therefore, the carbon dechlorination process is believed to be a very reliable process. The operation and monitoring of the system were also observed to be quite straightforward.

Regeneration of Dechlorination Carbon --

Typical results for the regeneration of the dechlorination carbon with a multiple hearth furnace system are presented in Table 13. The operating conditions of the furnace were maintained at the similar conditions normally used for the regeneration of carbon for wastewater treatment. It is clear from the results of the analyses of carbon characteristics that the dechlorination carbon was effectively reactivated to its virgin qualities. This was further supported by the fact that each sequence of operation produced a similar carbon capacity for dechlorination. Therefore, it is believed that the dechlorination carbon can be effectively regenerated with conventional thermal processes, such as multiple hearth furnace, under normal operating conditions.

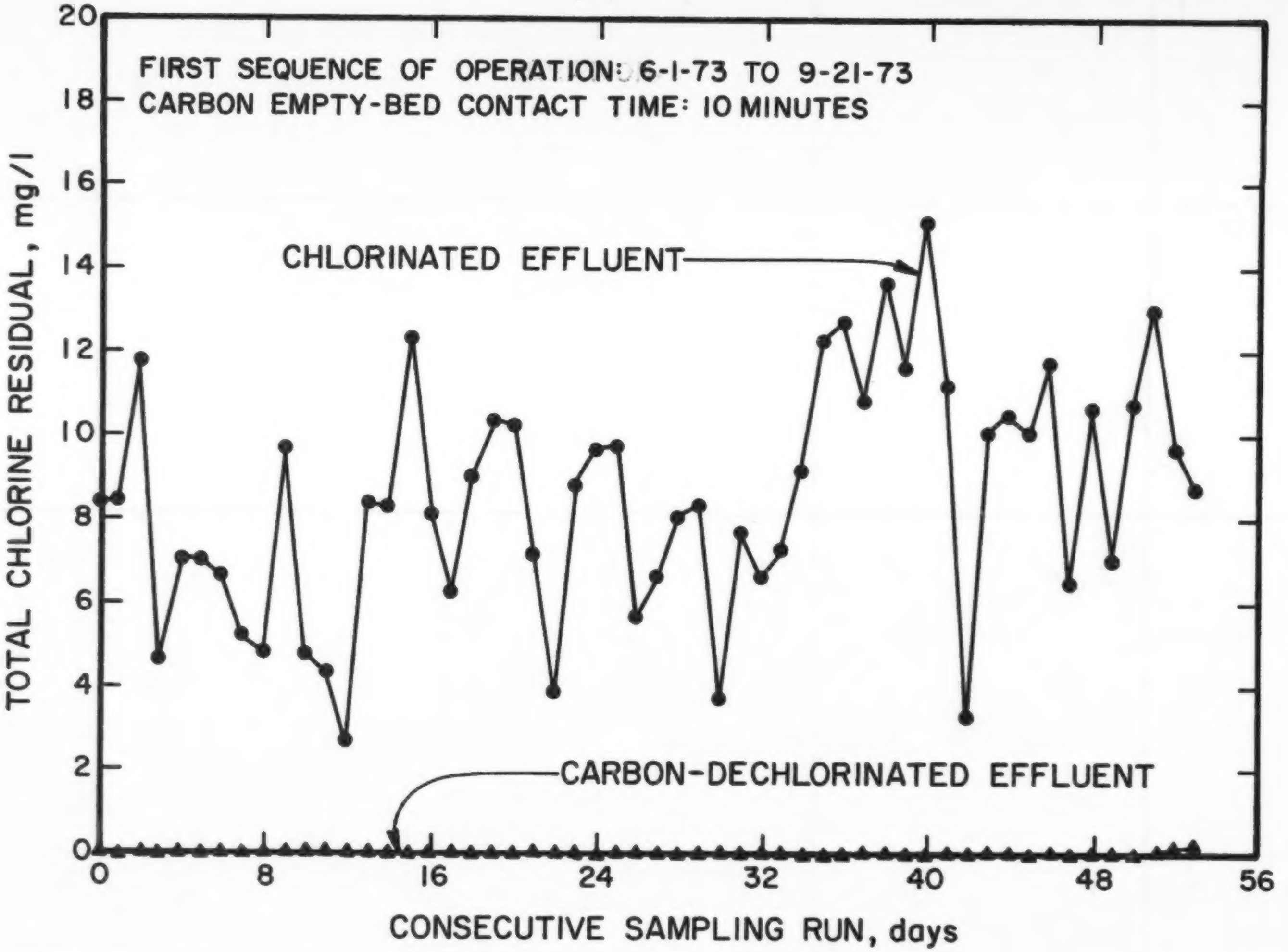

Figure 18. Chlorine residual of carbon-dechlorinated effluent.

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TABLE 13. REGENERATION OF DECHLORINATION CARBON (CALGON FILTRASORB 400)

Carbon Characteristics		Virgin carbon	Spent carbon composite sample	Regenerated carbon composite sample	
				Dry	Quenched
Iodine number, mg/g		723	625	711	695
Apparent density, g/cm³		0.456	0.512	0.473	0.458
Molasses number		206	287	321	375
Methylene blue no., mg/g		358	142	201	163
Ash, %		8.1	12.9	12.8	12.9
Sieve analysis:					
% Retained on sieve No.	8				
	12	0.1	1.2	1.3	1.1
	14	2.0	5.7	3.6	5.1
	16	34.3	24.7	13.9	21.7
	18	21.4	23.6	21.1	22.9
	20	13.0	17.4	27.3	17.6
	30	19.8	22.6	25.8	24.3
	40	8.4	4.4	6.3	6.8
	Pan	1.0	0.4	0.8	0.5

SECTION 7

PROCESS COST ESTIMATES

GENERAL

Cost estimates for three different dechlorination systems were prepared using the information gathered in the study. These were the sulfur dioxide, holding pond (estimate was made for pond instead of tank for practical application), and activated carbon adsorption dechlorination systems. In deriving the cost estimates, three levels of total chlorine residuals were used to cover a wider spectrum for meeting different disinfection standards in the nation. All the costs were based on meeting the 0.05 mg/l or less dechlorination requirement for maximizing the protection of aquatic life.

Three plant sizes of 43.8 l/sec (1 mgd), 219 l/sec (5 mgd) and 438 l/sec (10 mgd) were used in preparing the cost estimates for the various dechlorination processes. The process cost based on unit volume of processed water is believed to approach a leveling off value with plant size larger than 438 l/sec (10 mgd). Therefore, the three plant sizes used in these cost estimates may provide a general picture of the cost ranges for the three dechlorination processes investigated in this study.

An 8 percent interest rate was used for calculating the capital amortization cost for all three dechlorination processes. However, different amortization periods were used for different processes. The specific amortization periods used for the sulfur dioxide, holding pond and activated carbon adsorption dechlorination processes are 15, 30, and 20 years, respectively. The types and durabilities of the different structures normally used for the different dechlorination process plants have been considered in making the selection of an appropriate amortization period for each process cost estimate.

SULFUR DIOXIDE DECHLORINATION

Cost estimates for the sulfur dioxide dechlorination process under various operating and design conditions are summarized in Tables 14, 15, and 16. The sulfur dioxide to residual chlorine ($SO_2 : Cl_2$) dosage ratio was assumed to be 2 to 1 in the preparation of the cost estimates. No costs for pH adjustment and post dechlorination aeration were included in the process cost estimates, since these were not considered necessary for the dechlorination of domestic wastewater effluent.

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TABLE 14. SUMMARY OF SULFUR DIOXIDE DECHLORINATION COSTS
PLANT SIZE = 43.8 l/sec (1 mgd)

Cost Parameter	Influent residual chlorine, mg/l		
	0.5	5	10
Capital costs ($)			
SO_2 mixing & contact system	2,000	2,000	2,000
SO_2 feeding & control system	12,000	20,000	25,000
SO_2 handling & storage system	5,000	5,000	30,000
Sub-total	19,000	27,000	57,000
Electrical (10%)	1,900	2,700	5,700
Sub-total	20,900	29,700	62,700
Contingencies (20%)	4,180	5,940	12,540
Sub-total	25,080	35,640	75,240
Engineering (15%)	3,760	5,350	11,290
Total capital	28,840	40,990	86,530
Capital amortization (¢/m³)	0.24	0.35	0.73
O&M costs (¢/m³)			
SO_2 supply	0.03	0.26	0.55
Power	0.05	0.05	0.05
Labor	0.53	0.53	0.53
Maintenance materials	0.08	0.11	0.24
Water for SO_2 solution	0.03	0.03	0.03
Total O&M	0.72	0.98	1.40
Total process cost (¢/m³)	0.96	1.33	2.13

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TABLE 15. SUMMARY OF SULFUR DIOXIDE DECHLORINATION COSTS PLANT SIZE = 219 l/sec (5 mgd)

Cost parameter	Influent residual chlorine, mg/l		
	0.5	5	10
Capital costs ($)			
SO_2 mixing & contact system	4,000	4,000	4,000
SO_2 feeding & control system	20,000	25,000	30,000
SO_2 handling & storage system	5,000	30,000	30,000
Sub-total	29,000	59,000	64,000
Electrical (10%)	2,900	5,900	6,400
Sub-total	31,900	64,900	70,400
Contingencies (20%)	6,380	12,980	14,080
Sub-total	38,280	77,880	84,480
Engineering (15%)	5,740	11,680	12,670
Total capital	44,020	89,560	97,150
Capital amortization (¢/m³)	0.08	0.15	0.17
O&M costs (¢/m³)			
SO_2 supply	0.03	0.26	0.55
Power	0.05	0.05	0.05
Labor	0.11	0.11	0.11
Maintenace materials	0.03	0.05	0.05
Water for SO_2 solution	0.03	0.03	0.03
Total O&M	0.25	0.50	0.79
Total process cost (¢/m³)	0.33	0.65	0.96

TABLE 16. SUMMARY OF SULFUR DIOXIDE DECHLORINATION COSTS PLANT SIZE = 438 l/sec (10 mgd)

Cost parameter	Influent residual chlorine, mg/l		
	0.5	5	10
Capital costs ($)			
SO_2 mixing & contact system	10,000	10,000	10,000
SO_2 feeding & control system	20,000	30,000	40,000
SO_2 handling & storage system	5,000	30,000	30,000
Sub-total	35,000	70,000	80,000
Electrical (10%)	3,500	7,000	8,000
Sub-total	38,500	77,000	88,000
Contingencies (20%)	7,700	15,400	17,600
Sub-total	46,200	92,400	105,600
Engineering (15%)	6,930	13,860	15,840
Total capital	53,130	106,260	121,440
Capital amortization (¢/m^3)	0.04	0.09	0.10
O&M costs (¢/m^3)			
SO_2 supply	0.03	0.26	0.55
Power	0.05	0.05	0.05
Labor	0.05	0.05	0.05
Maintenance materials	0.03	0.03	0.03
Water for SO_2 solution	0.03	0.03	0.03
Total O&M	0.19	0.42	0.71
Total process cost (¢/m^3)	0.23	0.51	0.81

A detention time of 10 seconds was provided in the sulfur dioxide mixing and contact system to facilitate the complete reactions between sulfur dioxide and chlorine residual species. A mixer to provide an average of 2.0 kW (2.7 hp) per cubic meter of mixing volume was included in the cost estimate. A minimal labor of 2 hours per day was assumed for the operation and maintenance of the dechlorination system for all three sizes of plants.

As indicated in Tables 14 through 16, the total process cost estimates range from 0.23 cents/m^3 (0.87 cents/1000 gal) to 2.13 cents/m^3 (8.06 cents/1000 gal), depending on the size of plant and concentration of influent chlorine residual. The effects of these factors on the process cost estimates are illustrated in Figure 19. The cost curves indicate that the process costs for sulfur dioxide dechlorination approach minimum levels when the plant sizes are larger than 438 l/sec (10 mgd).

HOLDING POND DECHLORINATION

According to Figure 14, the necessary detention times for dissipation of 0.5, 5 and 10 mg/l total influent chlorine residuals in a holding pond are approximately 9.6, 96 and 192 hours, respectively. In the cost estimates, a water depth of 1.83 m (6 ft) was assumed for the pond construction. A layer of 10 cm (4 in) gravel lining was provided for the holding pond. Table 17 summarizes the cost estimates for various operating conditions for the holding pond dechlorination process. The associated unit costs for operation and maintenance are listed in Table 18. The daily labor required for operation and maintenance was assumed to be 2 hours for 43.8 l/sec (1 mgd) plant and 4 hours for both 219 l/sec (5 mgd) and 438 l/sec (10 mgd) plants.

As indicated in Table 17, the total process costs for holding pond dechlorination process range from 0.22 cents/m^3 (0.83 cents/1000 gal) to 2.58 cents/m^3 (9.77 cents/1000 gal). The proportion of the capital amortization cost to the total process cost is as high as 95 percent for the case of 10 mg/l chlorine residual in a 438 l/sec (10 mgd) plant. Table 19 was prepared to demonstrate the effects of major capital items, such as land, excavation and lining costs, on the capital amortization costs. The table indicates that the total capital amortization cost for a 438 l/sec (10 mgd) plant with 10 mg/l influent chlorine residual can be reduced from 2.02 cents/m^3 (7.65 cents/1000 gal) to 0.30 cents/m^3 (1.14 cents/1000 gal), an 85 percent reduction, depending on land and construction conditions.

CARBON ADSORPTION DECHLORINATION

The following general operating conditions were assumed in making the various cost estimates for the carbon adsorption dechlorination process:

1. Carbon capacity for dechlorination = 0.2 kg chlorine residual per kg of carbon (0.2 lb Cl_2/lb carbon).

2. Carbon regeneration loss = 7 percent per regeneration.

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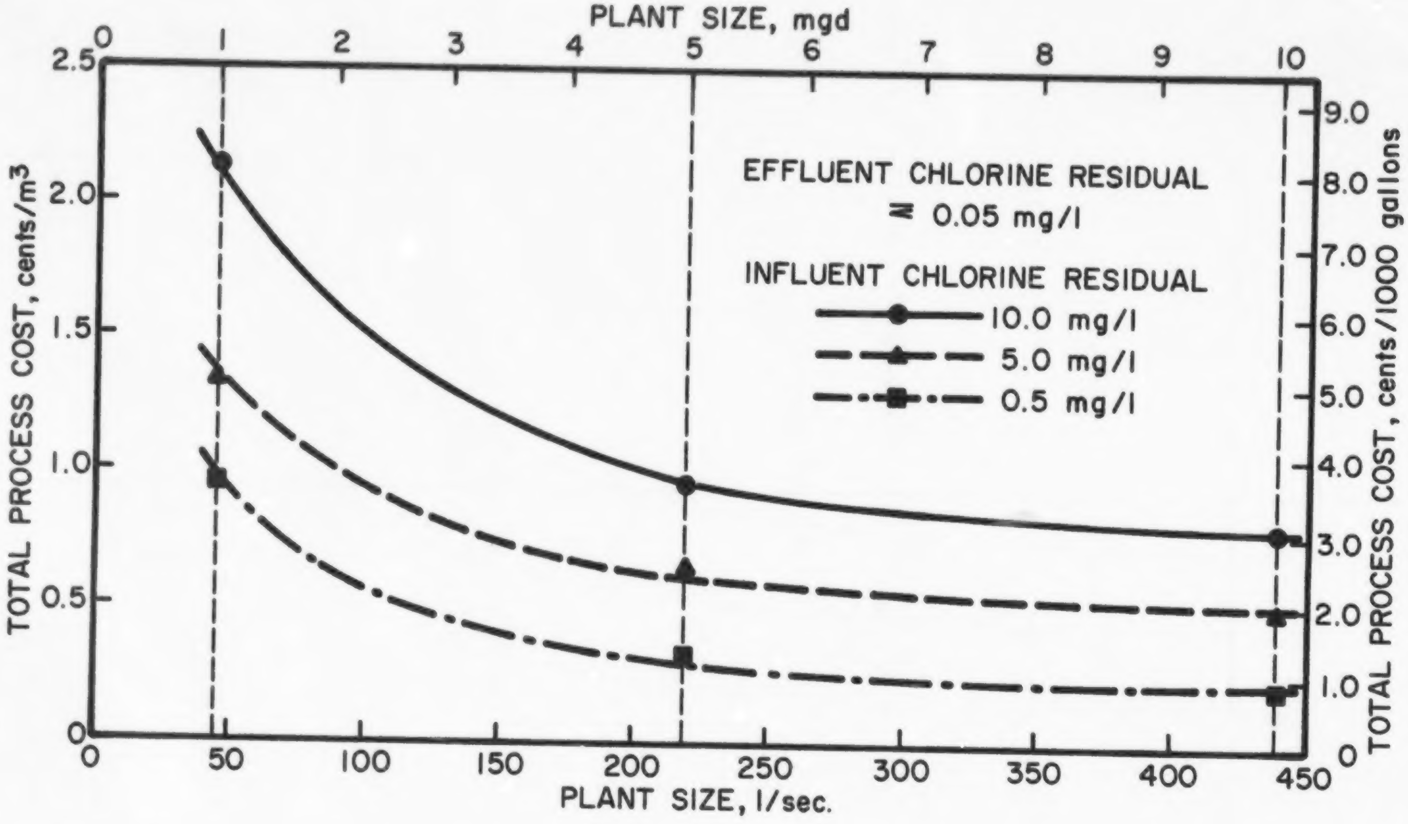

Figure 19. Process cost curves for sulfur dioxide dechlorination.

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TABLE 17. PROCESS COST ESTIMATES FOR HOLDING POND DECHLORINATION

Plant size (mgd)	Residual chlorine (mg/l)	Pond volume (1000 ft^3)	Land area (acre)	Land cost (1000$)	Excavation & hauling cost (1000$)	Lining cost (1000$)	Piping & other cost (1000$)	Total capital cost (1000$)	Process cost estimate (¢/m^3)		
									Capital amorti-zation	Operation & maintenance	Total process cost
	0.5	53	0.4	8	3.5	4.4	5.0	20.9	0.13	0.53	0.66
1	5	533	4.1	82	31.7	43.6	5.0	162.3	1.04	0.53	1.57
	10	1,067	8.4	168	63.3	87.1	5.0	318.4	2.05	0.53	2.56
	0.5	267	2.1	42	17.8	21.8	10.0	81.6	0.10	0.21	0.31
5	5	2,672	20.8	416	158.0	217.7	10.0	801.7	1.03	0.21	1.24
	10	5,329	41.6	832	296.5	435.4	10.0	1,573.9	2.02	0.21	2.23
	0.5	533	4.1	82	31.6	43.6	15.0	172.2	0.11	0.11	0.22
10	5	5,329	41.6	832	296.5	435.4	15.0	1,573.9	1.01	0.11	1.12
	10	10,672	83.3	1,666	592.8	870.6	15.0	3,144.4	2.02	0.11	2.13

Notes: 1 mgd = 43.3 l/sec; 1,000 ft^3 = 28.3 m^3; 1 acre = 0.405 ha.

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TABLE 18. UNIT COSTS FOR OPERATION AND MAINTENANCE COST ESTIMATES

Sulfur dioxide	$\$/\mathrm{lb}$	0.13
Activated carbon	$\$/\mathrm{lb}$	0.75
Power	¢/kWh	5.0
Fuel	¢/therm	18.0
Backwash water	¢/1,000 gallons	3.0
Water supply	¢/1,000 gallons	60.0
Labor	$\$/\mathrm{hr}$	10.0
Excavation & hauling	$\$/\mathrm{yd}^3$	
	$<1{,}000\ \mathrm{yd}^3$	2.0
	$1{,}000 \sim 10{,}000\ \mathrm{yd}^3$	1.8
	$10{,}000 \sim 100{,}000\ \mathrm{yd}^3$	1.6
	$<100{,}000\ \mathrm{yd}^3$	1.5
Lining cost (gravel)	¢/ft^2	20.0

Notes:
1 lb = 0.454 kg;
1 gal = 3.785 l;
1 yd^3 = 0.765 m^3;
1 therm = 105,500 kJ;
1 acre = 0.405 ha;
1 ft^2 = 0.093 m^2;

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TABLE 19. EFFECTS OF COST PARAMETERS ON CAPITAL AMORTIZATION FOR HOLDING POND DECHLORINATION PROCESS

Plant size (mgd)	Residual chlorine (mg/1)	Capital Amortization cost, ¢/m^3			
		Case 1	Case 2	Case 3	Case 4
1	0.5	0.13	0.09	0.06	0.06
	5	1.04	0.56	0.28	0.19
	10	2.05	1.12	0.55	0.34
5	0.5	0.10	0.07	0.03	0.03
	5	1.03	0.54	0.26	0.17
	10	2.02	1.06	0.51	0.30
10	0.5	0.11	0.06	0.04	0.02
	5	1.01	0.52	0.24	0.15
	10	2.02	1.06	0.49	0.30

Notes: Case 1 - Land cost @ \$49,400/ha (\$20,000/acre) with provision for excavation, hauling, lining, piping and miscellaneous costs.

Case 2 - Same as Case 1, except land cost @ \$4,940/ha (\$2,000/acre).

Case 3 - Land cost @ \$4,940/ha (\$2,000/acre) with provision for excavation, hauling, piping and miscellaneous costs only.

Case 4 - Same as Case 3, except no provision for hauling cost.

3. Fuel consumption in carbon regeneration = 9,280 kJ per kg of carbon regenerated (4,000 BTU/lb carbon).

4. Power consumption = 80 kWh Per 1,000 m^3 (300 kWh per million gallons).

5. Carbon empty-bed contact time = 10 minutes.

6. A multiple hearth furnace with afterburner and Venturi wet scrubber air pollution control system was used as carbon regeneration system.

7. Gravity concrete tank was used as carbon contact system.

8. The annual labor ranges from 4,360 hours to 7,240 hours depending on the operating conditions.

9. Calgon Filtrasorb 400 granular activated carbon was used.

Tables 20 through 22 are the summaries of the cost estimates for carbon adsorption dechlorination process. The total process costs range from 2.91 cents/m^3 (11.01 cents/1000 gal) to 11.10 cents/m^3 (42.01 cents/1000 gal) as indicated in the tables.

COST COMPARISONS

The cost estimates for sulfur dioxide, holding pond and carbon adsorption dechlorination processes are summarized in Table 23. As indicated in both Table 23 and Figure 20, the carbon adsorption dechlorination process is estimated to be substantially more expensive than the other two processes in all cases. Therefore, the carbon adsorption process seems to be economically unfeasible for being used solely for meeting a dechlorination requirement. However, the carbon adsorption process may be considered as a potentially cost-effective treatment process when removal of trace organics and dechlorination are required at the same time.

The holding pond and sulfur dioxide dechlorination process are competitive for various size plants with low influent chlorine residuals, as indicated in Table 23. The holding pond dechlorination becomes more cost-effective than sulfur dioxide dechlorination process when inexpensive land can be obtained and simpler pond construction can be allowed. The presence of good sunlight is also considered an important criterion for successful use of holding pond dechlorination process. Considerable savings in operating and maintenance costs are also obtainable with the holding pond dechlorination process. Figure 21 compares the sulfur dioxide with the holding pond dechlorination process under various cost alternatives as described in Table 19.

Under normal conditions, the sulfur dioxide dechlorination is believed to be the most cost-effective process for meeting the effluent residual chlorine standards. This is believed to be especially true for the State of California where the land cost is very expensive and the bacterial standards are very stringent.

TABLE 20. SUMMARY OF CARBON ADSORPTION DECHLORINATION COSTS PLANT SIZE = 43.8 l/sec (1 mgd)

Cost parameter	Influent residual chlorine, mg/l		
	0.5	5	10
Capital costs ($)			
Pumping & piping system	40,000	40,000	40,000
Initial carbon charge	23,000	23,000	23,000
Carbon contacting system	150,000	150,000	150,000
Carbon regeneration system	80,000	200,000	250,000
Sub-total	293,000	413,000	463,000
Electrical (10%)	29,000	41,000	46,000
Instrumentation (5%)	15,000	21,000	23,000
Sub-total	337,000	475,000	532,000
Contingencies (20%)	67,000	95,000	106,000
Sub-total	404,000	570,000	638,000
Engineering (15%)	61,000	86,000	96,000
Total capital	465,000	656,000	734,000
Capital amortization (¢/m³)	3.43	4.84	5.41
O&M costs (¢/m³)			
Carbon makeup	0.03	0.29	0.58
Backwash water	0.03	0.03	0.03
Power	0.40	0.40	0.40
Fuel	0.03	0.05	0.08
Labor	3.17	3.67	4.20
Maintenance materials	0.24	0.34	0.40
Total O&M	3.90	4.78	5.69
Total process cost (¢/m³)	7.33	9.62	11.10

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TABLE 21. SUMMARY OF CARBON ADSORPTION DECHLORINATION COSTS PLANT SIZE = 219 l/sec (5 mgd)

Cost parameter	Influent residual chlorine, mg/l		
	0.5	5	10
Capital cost ($)			
Pumping & piping system	100,000	100,000	100,000
Initial carbon charge	113,000	113,000	113,000
Carbon contacting system	650,000	650,000	650,000
Carbon regeneration system	200,000	450,000	600,000
Sub-total	1,063,000	1,313,000	1,463,000
Electrical (10%)	106,000	131,000	146,000
Instrumentation (5%)	53,000	66,000	73,000
Sub-total	1,222,000	1,510,000	1,682,000
Contingencies (20%)	244,000	302,000	336,000
Sub-total	1,466,000	1,812,000	2,018,000
Engineering (15%)	220,000	272,000	303,000
Total capital	1,686,000	2,084,000	2,321,000
Capital amortization (¢/m^3)	2.49	3.07	3.42
O&M costs (¢/m^3)			
Carbon makeup	0.03	0.29	0.58
Backwash water	0.03	0.03	0.03
Power	0.40	0.40	0.40
Fuel	0.03	0.05	0.08
Labor	0.63	0.74	0.85
Maintenance materials	0.18	0.21	0.24
Total O&M	1.30	1.72	2.18
Total Process cost (¢/m^3)	3.79	4.79	5.60

TABLE 22. SUMMARY OF CARBON ADSORPTION DECHLORINATION COSTS PLANT SIZE = 438 l/sec (10 mgd)

Cost parameter	Influent residual chlorine, mg/l		
	0.5	5	10
Capital costs ($)			
Pumping & piping system	150,000	150,000	150,000
Initial carbon charge	230,000	230,000	230,000
Carbon contacting system	960,000	960,000	960,000
Carbon regeneration system	300,000	500,000	600,000
Sub-total	1,640,000	1,840,000	1,940,000
Electrical (10%)	164,000	184,000	194,000
Instrumentation (5%)	82,000	92,000	97,000
Sub-total	1,886,000	2,116,000	2,231,000
Contingencies (20%)	377,000	423,000	446,000
Sub-total	2,263,000	2,539,000	2,677,000
Engineering (15%)	339,000	381,000	402,000
Total capital	2,602,000	2,920,000	3,079,000
Capital amortization (¢/m³)	1.92	2.15	2.27
O&M costs (¢/m³)			
Carbon makeup	0.03	0.29	0.58
Backwash water	0.03	0.03	0.03
Power	0.40	0.40	0.40
Fuel	0.03	0.05	0.08
Labor	0.37	0.42	0.53
Maintenance materials	0.13	0.16	0.16
Total O&M	0.99	1.35	1.78
Total process cost (¢/m³)	2.91	3.50	4.05

TABLE 23. SUMMARY OF DECHLORINATION PROCESS COST ESTIMATES

Plant size (mgd)	Residual chlorine mg/l	Cost item	Sulfur dioxide (¢/m^3)	Holding pond (¢/m^3)	Carbon adsorption (¢/m^3)
1	0.5	Capital	0.24	0.13	3.43
		O&M	0.72	0.53	3.90
		Total	0.96	0.66	7.33
	5	Capital	0.35	1.04	4.84
		O&M	0.98	0.53	4.78
		Total	1.33	1.57	9.62
	10	Capital	0.73	2.05	5.41
		O&M	1.40	0.53	5.69
		Total	2.13	2.58	11.10

TABLE 23. SUMMARY OF DECHLORINATION PROCESS COST ESTIMATES (Cont.)

Plant size (mgd)	Residual chlorine mg/l	Cost item	Sulfur dioxide (¢/m³)	Holding pond (¢/m³)	Carbon adsorption (¢/m³)
5	0.5	Capital	0.08	0.10	2.49
		O&M	0.25	0.21	1.30
		Total	0.33	0.31	3.79
	5	Capital	0.15	1.03	3.07
		O&M	0.50	0.21	1.72
		Total	0.65	1.24	4.79
	10	Capital	0.17	2.02	3.42
		O&M	0.79	0.21	2.18
		Total	0.96	2.23	5.60

TABLE 23. SUMMARY OF DECHLORINATION PROCESS COST ESTIMATES (Cont.)

Plant size (mgd)	Residual chlorine mg/l	Cost item	Sulfur dioxide (¢/m³)	Holding pond (¢/m³)	Carbon adsorption (¢/m³)
10	0.5	Capital	0.04	0.11	1.92
		O&M	0.19	0.11	0.99
		Total	0.23	0.22	2.91
	5	Capital	0.09	1.01	2.15
		O&M	0.42	0.11	1.35
		Total	0.51	1.12	3.50
	10	Capital	0.10	2.02	2.27
		O&M	0.71	0.11	1.78
		Total	0.81	2.13	4.05

Note: 1 mgd = 43.8 l/sec.

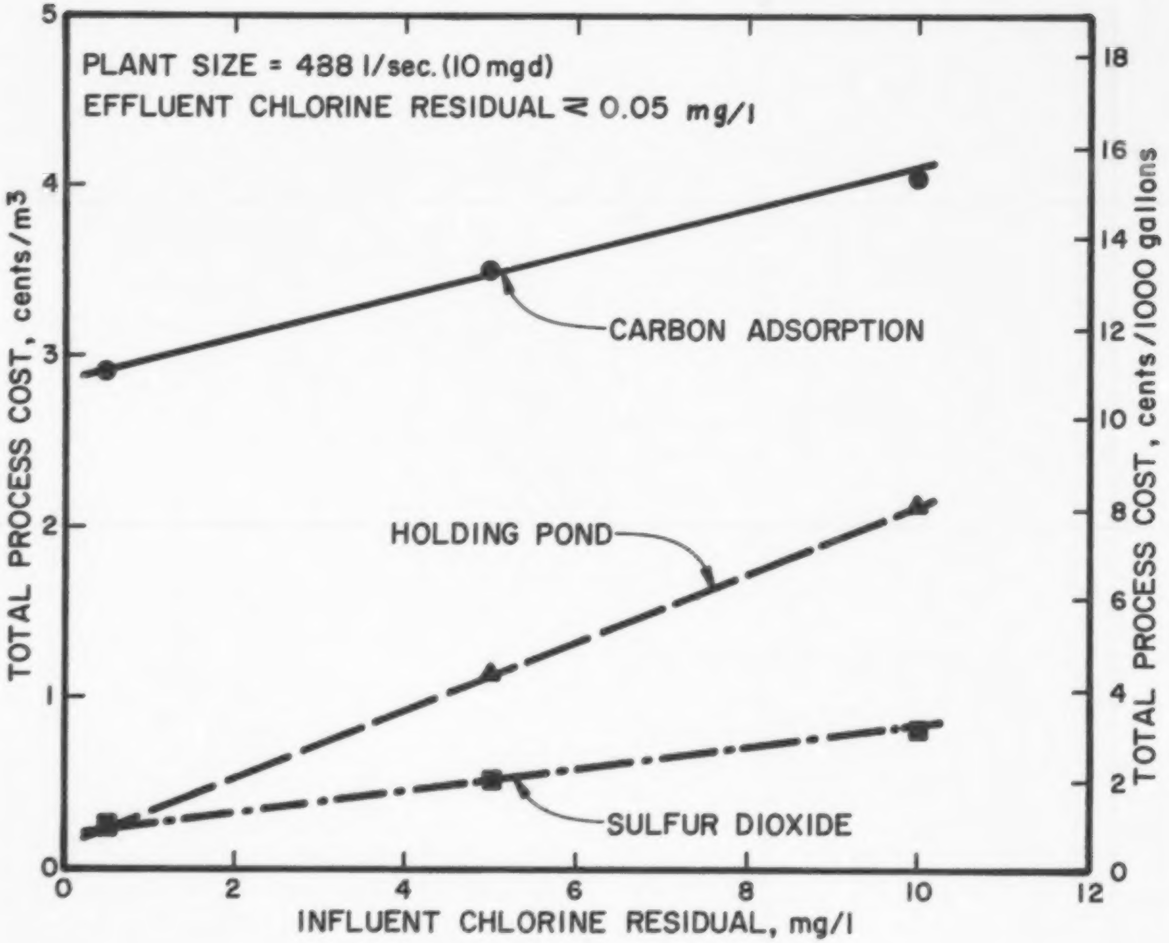

Figure 20. Process cost comparison among different dechlorination processes.

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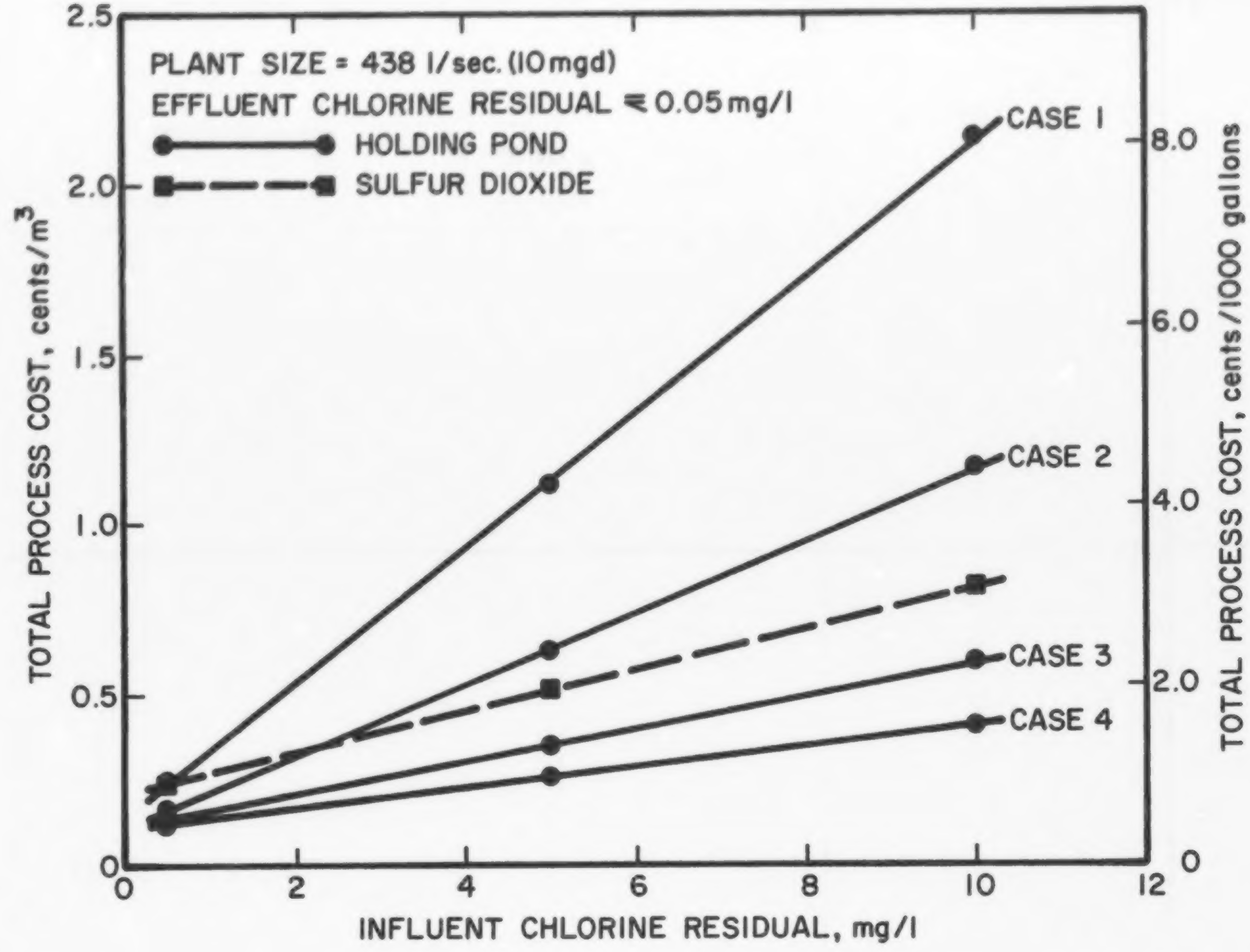

Figure 21. Cost comparison between sulfur dioxide and holding pond dechlorination processes under different cost assumptions as described in Table 19.

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APPENDIX. DECHLORINATION FIELD SURVEY QUESTIONNAIRE

SULFUR DIOXIDE DECHLORINATION FIELD SURVEY

Conducted By
County Sanitation Districts of Los Angeles County
Under
U. S. EPA Contract No. 14-12-150

I. General Information:

(a) Name of Agency ____________________

Person Replying to Questionnaire ____________________

Title ____________________ Phone ____________________

Address ____________________

(b) Name of Treatment Plant ____________________

Address ____________________

Plant Type: Primary [ ] Secondary [ ] Tertiary [ ] Ponds [ ]

Plant Flow (mgd): Minimum Daily ____________ Maximum Daily ____________

Average Daily ____________ Design Capacity ____________

(c) Discharge Standard: Total Coliform (MPN/100 ml) ____________

Total Chlorine Residual (mg/l) ____________

(d) Sulfur Dioxide Capacity (lbs/day) ____________ No. of Sulfonators ____________

Startup Date ____________ Construction Cost ____________

II. Engineering Design Information

(a) Firm Designing Dechlorination System ____________________

Address ____________________

Design Engineer ____________________ Phone ____________________

(b) SO_2 Feed Control System (please provide drawings)

Equipment Manufacturer: W/T [ ] F/P [ ] Others (specify) ____________

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APPENDIX. DECHLORINATION FIELD SURVEY QUESTIONNAIRE (CONT.)

II. (Continued)

(b) Feedforward [ ] Feedback [ ] Others (specify) ______________________

Flow Paced [ ] Residual Control [ ]

Flow and Residual Control [ ]

Flow Signal: Pneumatic [ ] Electric [ ]

Dosage Signal: Pneumatic [ ] Electric [ ]

Residual Controller: Gap [ ] Proportional and Reset [ ] None [ ]

Multiplier: Yes [ ] No [ ] Adjustable Slope Factor Yes [ ] No [ ]

No. of Analyzers ______________ Manufacturer ______________

Analyzer Range (as mg/l $C1_2$ Residual) ______________________

Analyzer Sampling Points ______________________

Lagtime (mins.) ______________ Flow Meter Location ______________

What is the most unique feature of your feed control design?

____

____

(c) SO_2 Mixing Chamber: Yes [ ] No [ ] Detention Time (mins.) ______________

SO_2 Injection Device: Diffuser [ ] Others (specify) ______________

SO_2 Mixer Type: Mechanical [ ] Hydraulic Jump [ ]

Parshall Flume [ ] None [ ]

Reaeration: Yes [ ] No [ ] pH Adjustment: Yes [ ] No [ ]

(d) Why did you decide on SO_2 for dechlorination? ______________________

____

____

III. Operational Information

(a) Is dechlorination system operated daily (24 hours/day)?

Yes [ ] No [ ]

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APPENDIX. DECHLORINATION FIELD SURVEY QUESTIONNAIRE (CONT.)

III. (Continued)

(b) Is overdosing of SO_2 commonly employed to meet residual discharge standard?

Yes [ ] No [ ] Please explain ______________________________

____

____

(c) What is the SO_2/Cl_2 (lb/lb) ratio requirement of the plant? ______________________________

(d) How much SO_2 (lbs) does your plant use monthly? ______________________________

(e) Is the SO_2 feed control system reliable? Yes [ ] No [ ]

Please explain ______________________________

____

(f) Will the SO_2 feed control system handle drastic changes in chlorine residual due to plant upset or equipment malfunction? Yes [ ] No [ ]

Please explain ______________________________

____

(g) Who calibrates the chlorine residual analyzer? Operator [ ] Chemist [ ] Others (specify) ______________________________

By what method? Amperometric Titration [ ] Starch Iodide [ ]

Colorimetric OT [ ] Or DPD [ ] Forward Titration [ ] Back Titration [ ]

(h) Do you have analyzer charts of residual chlorine before and after dechlorination available for inspection? Yes [ ] No [ ]

(i) Is there any unusual biological growth after dechlorination or slime buildup in outfall pipe?

Yes [ ] No [ ]

(j) Is your plant open for a visit? Yes [ ] No [ ]

IV. Water Quality Data: Weekly [ ] Monthly [ ] Yearly [ ]

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APPENDIX. DECHLORINATION FIELD SURVEY QUESTIONNAIRE (CONT.)

Parameter	End of Chlorine Contact Tank	After SO_2 Addition	After Aeration and pH adjustment
Total Cl_2 Res., (mg/1)			
Total Coliform (MPN/100 m1)			
pH			
Dissolved Oxygen (mg/1)			
Alkalinity (mg/1)			
TDS (mg/1)			

V. Additional Comments: ____________________

Please return to: MR. John D. Parkhurst
Chief Engineer and General Manager
County Sanitation Districts of Los Angeles County
Pomona Research Facility
295 Humane Way
Pomona California 91766

Attention: Mr. Henry B. Ghan
Project Engineer

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